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SHIPBOARD CALIBRATION NETWORK EXTENSION UTILIZING COTS PRODUCTS

by

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13. ABSTRACT (maximum 200 words)

The feasibility of a concept of operation to reduce the manpower required during shipboard sensor calibration is investigated in this thesis. The proposed calibration process takes into consideration security concerns and the layout of the ship whereby cables cannot be laid across decks and stairways.

The current calibration process requires at least two technicians, one to read the sensor information displayed on the Machinery Control System (MCS) located on one deck and another to man the reference sensor installed on a different deck. In this thesis, IEEE 802.11 wireless LAN in connection with a Keyboard Video Monitor (KVM) switch is proposed to transmit the sensor information displayed on the MCS to the technician manning the reference sensor, reducing the required manpower to one. The range and number of repeaters used to extend the wireless network is investigated in this thesis to determine the feasibility of this concept of operation.

From the experimental results, we concluded that the proposed concept of operation is feasible for calibration processes that rely on steady-state readings rather than transient responses.

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SHIPBOARD CALIBRATION NETWORK EXTENSION UTILIZING COTS PRODUCTS

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The feasibility of a concept of operation to reduce the manpower required during shipboard sensor calibration is investigated in this thesis. The proposed calibration process takes into consideration security concerns and the layout of the ship whereby cables cannot be laid across decks and stairways.

The current calibration process requires at least two technicians, one to read the sensor information displayed on the Machinery Control System (MCS) located on one deck and another to man the reference sensor installed on a different deck. In this thesis, IEEE 802.11 wireless LAN in connection with a Keyboard Video Monitor (KVM) switch is proposed to transmit the sensor information displayed on the MCS to the technician manning the reference sensor, reducing the required manpower to one. The range and number of repeaters used to extend the wireless network is investigated in this thesis to determine the feasibility of this concept of operation.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACK	Acknowledgement
AP	Access point
COTS	Commercial-off-the shelf
DHCP	Dynamic Host Configuration Protocol
DNS	Domain Name Server
DVI	Digital Visual Interface
GUI	Graphical User Interface
H&ME	Hull, mechanical, and electrical
KVM	Keyboard Video and Mouse
LAN	Local Area Network
MCS	Machinery Control Systems
NIST	National Institute of Standards and Technology
RDP	Remote Desktop Protocol
RFB	Remote Frame Buffer
RSSI	Received Signal Strength Indicator
RTO	Retransmission timeout
SSID	Service Set Identification
TCP	Transport Control Protocol
VNC	Virtual Network Computing
WLAN	Wireless Local Area Network

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EXECUTIVE SUMMARY

Current DDG ships have approximately 3,742 hull, mechanical, and electrical (H&ME) sensors. Of these sensors, approximately 2,669 require periodic calibration. More than half of these sensors are integral parts of the shipboard's Machinery Control Systems (MCS), which can only be read at the system consoles, usually located a deck above the sensor location.

The reliability and operational readiness of the ship depends on the accuracy of shipboard sensors such as pressure and temperature sensors; hence, periodic checks and calibrations must be performed on these sensors to ensure data integrity. Currently, each calibration task requires at least two technicians to complete the task. One technician is required to read the sensor output displayed on the system console, and one technician is required to read the reference sensor output, both physically separated. These sensor readings are then transmitted using hand-held radio communications like walkie-talkies between the two technicians.

The U.S. Navy emphasizes the need to reduce future crew sizes without increasing labor hours; hence, a new calibration process is proposed in this thesis. The research work was conducted to establish the feasibility of adopting COTS components to reduce the man-hours required for the calibration of sensors without using the shipboard Local Area Network (LAN) and taking into account the layout of the ship and its security constraints.

The hardware used in the proposed concept of operation is shown in Figure 1. The desktop computer emulates the MCS system console. It connects to the Keyboard Video Monitor (KVM) switch, which has embedded Virtual Network Computing (VNC) server software; hence, the technician does not require the MCS system console's user authentication to view the display remotely. This non-invasive method of viewing the MCS system console should alleviate the U.S. Navy's security concern. The LAN output on the KVM allows it

to interface to the 802.11 router, forming part of a separate and isolated wireless network created for the calibration of sensors. This temporary wireless network, which is independent of the shipboard's LAN, will not threaten the shipboard's network security. Using this wireless network, the system console display can be transmitted wirelessly via the wireless access point (AP) and repeaters to the technician stationed at the reference sensor instruments readout. The technician will be able to view the MCS system console display on a Windows-based hand-held portable tablet that has the VNC client software installed. The Windows-based platform facilitates software development and testing since most programming platforms and testing kits are compatible with the Windows operating system.

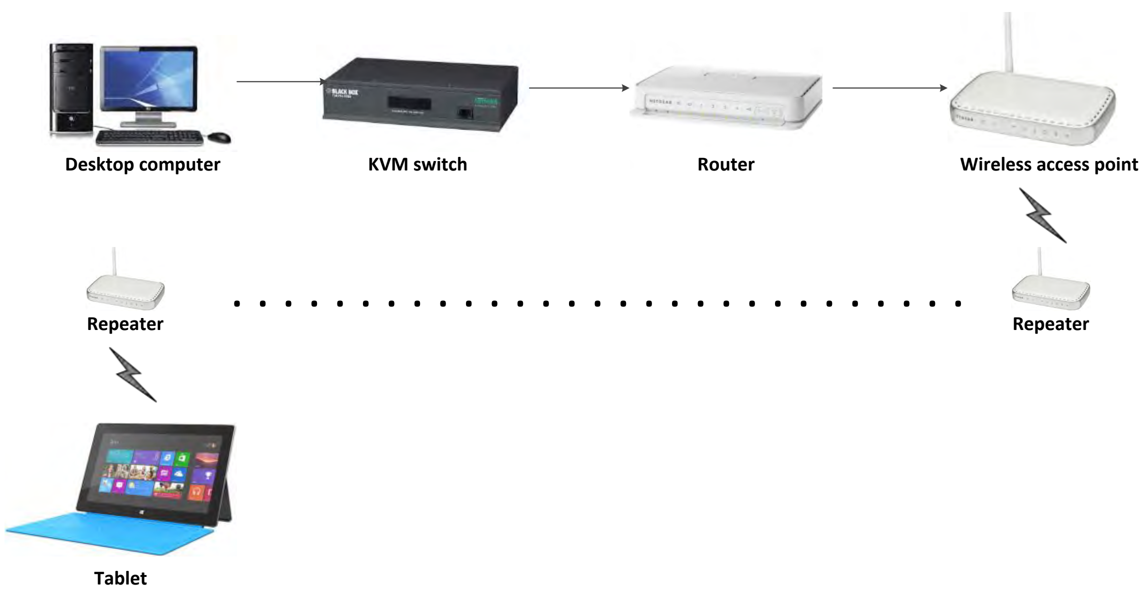

Figure 1. Hardware setup.

The success of this concept of operation is dependent on the wireless range that it is able to achieve. The experiments in this thesis were designed to measure the throughput and various Transport Control Protocol (TCP) parameters to determine the feasibility of using repeaters to extend the range of the wireless network. The repeaters act as relay points for frames travelling between the wireless AP and the tablet. However, a repeater receives and retransmits the frames using the same radio; hence, each repeater reduces the bandwidth that is available to it by at least 50 percent. When adding repeaters in the wireless network, the tradeoff between range and speed must be considered.

The experiment was conducted in Naval Postgraduate School's Spanagel Hall's stairways, which have five levels. The following configurations were tested to establish the impact of repeaters on the range of the network:

- No repeaters
- One repeater at Level 1.5
- One repeater at Level 2.5
- One repeater at Level 3.5
- Two repeaters – One at Level 2.5 and one at Level 1.5
- Two repeaters – One at Level 3.5 and one at Level 1.5
- Two repeaters – One at Level 3.5 and one at Level 2.5
- Three repeaters – One at Level 3.5, one at Level 2.5 and one at Level 1.5.

From the throughput and TCP parameter measurements, it was observed that the most optimal configuration is when three repeaters were used, and the least optimal configuration is when no repeaters were used. Due to the limited number of levels in Spanagel Hall, a maximum of three repeaters could be used. From the measurements, there was no degradation when three repeaters were used, and this suggests that more repeaters can be added to further increase the wireless network range.

The proposed concept of operation works to reduce the manpower required for the calibration process from two technicians to one technician, addressing the U.S. Navy's emphasis on reducing future crew sizes.

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I. INTRODUCTION

A. BACKGROUND

The reliability and operational readiness of a ship depends on the accuracy of its shipboard sensors such as pressure and temperature sensors since these sensor readings provide indication on the health of the machinery onboard the ships; hence, it is important for sensors to provide accurate readings. To achieve this, periodic checks and calibrations must be performed on these sensors to ensure data integrity.

In current DDG ships, there are approximately 3,742 hull, mechanical, and electrical (H&ME) sensors [1]. Of these sensors, approximately 2,669 require periodic calibration [1]. More than half of these sensors are integral parts of the shipboard's Machinery Control Systems (MCS), which can only be read at the system consoles, usually located a deck above the sensor location [1].

Calibrating these sensors requires thousands of man-hours from specialized technicians. Each calibration task requires at least two technicians to complete the job [1].

With emphasis being placed on reducing future crew sizes without increasing labor hours [1] , which translates to reducing the amount of man-hours spent on calibrating sensors, a new calibration procedure is needed.

The current wireless and digital technologies present a potential solution to address the U.S. Navy's concern for its man-hour requirement. By utilizing commercial-off-the shelf (COTS) equipment, we are able to streamline the calibration process to make available the digital data displayed on the MCS system console available at the location of the sensor to be calibrated.

With the wide adoption of the wireless local area network (WLAN) protocol, IEEE 802.11 standard devices have been proven to provide a stable, wireless infrastructure for many applications. The fast setup, wire-free configuration and sufficient bandwidth make 802.11 devices optimal for consideration. Utilizing 802.11 devices as part of the solution to wirelessly transmit data, we are able to reduce man-hour requirements by increasing efficiency in the calibration process.

B. CURRENT CALIBRATION PROCESS

The importance of having accurate sensor readings was emphasized in the previous section. Sensors are typically calibrated based on the time interval specified by the manufacturer or adjusted based on historical observations.

To be able to calibrate the sensors to provide accurate readings, there must be a reference sensor that provides “higher accuracy to detect, correlate, adjust, rectify, and document the accuracy” of the sensor being compared [2]. This process is mandated by the National Institute of Standards and Technology (NIST). It is part of the U.S. Department of Commerce and is responsible for upholding the standards of reference metrics in the United States. Reference sensors used in the calibration process have to be traceable to the NIST or equivalent. Reference sensors are said to be traceable to the NIST standards if the following conditions are met:

- “An unbroken chain of measurements back to NIST standards is maintained” [3].
- “Each step of the chain has known and documented uncertainties” [3].
- “There is a quality system to ensure that the reference sensors and associated measurement equipment maintain their measurement uncertainty (accuracy)” [3].

The traceability path of a reference temperature sensor is illustrated in Figure 1. As described in the figure, the temperature sensor in red is calibrated against a NIST Standard temperature sensor in blue which has a magnitude higher resolution. The process then continues and records are kept for the measurements.

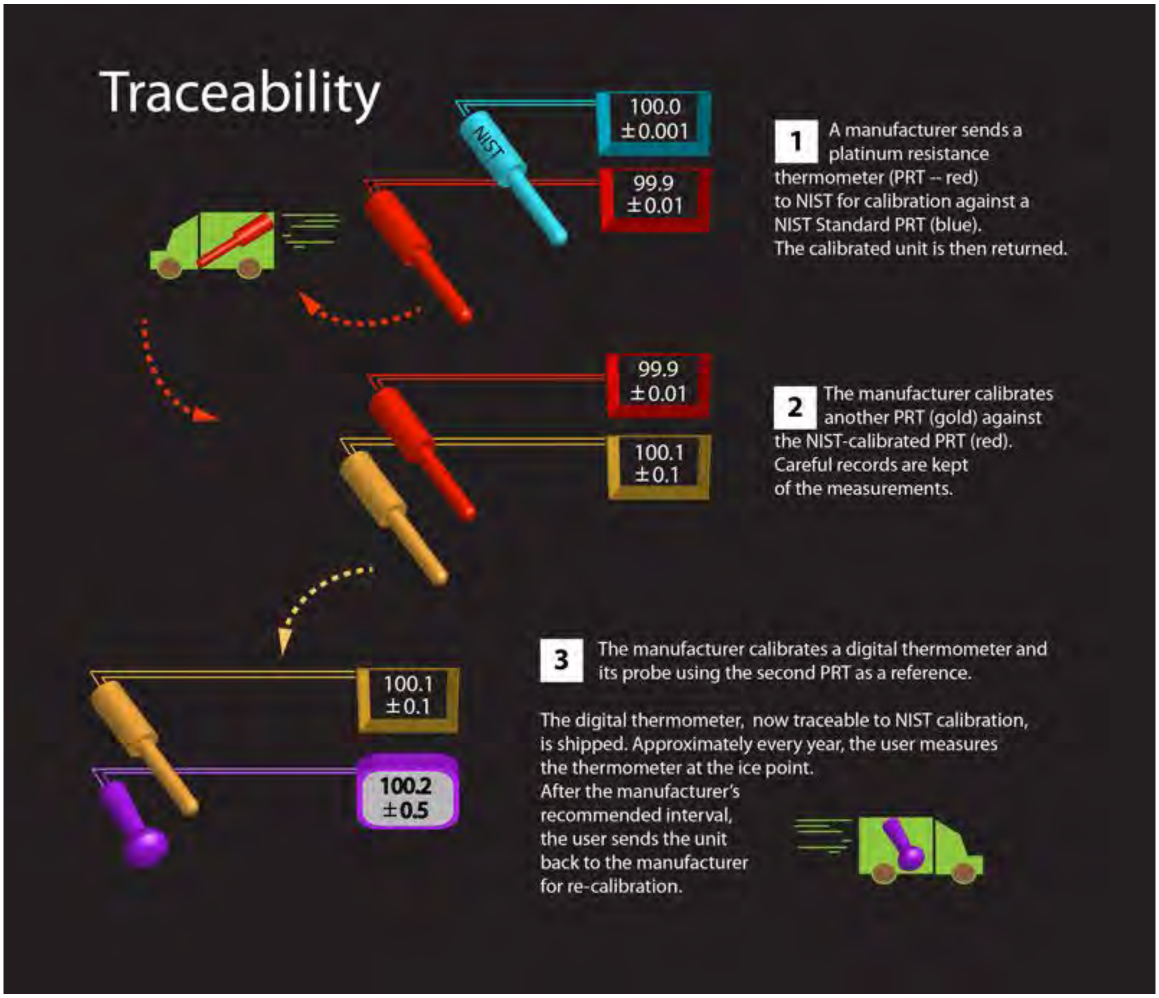

Figure 1. Traceability of reference temperature sensor, from [3].

Onboard ships, the sensor calibration process is manual, time consuming and labor intensive. It requires at least two technicians to complete the task. The system console, which displays the sensor output, and the sensor to be calibrated are physically separated. The reference sensor is typically installed close to the sensor to be calibrated, as the two sensors should be exposed to the same conditions as practically as possible. For example, to calibrate a pressure sensor, the valves of the pipes can be closed to isolate the sensor to be calibrated. A calibration pump, which serves as a pressure source, is installed in the same compartment of the pipe as the reference sensor and the sensor to be calibrated. One technician is required to read the sensor output displayed on the system console, and one technician is required to read the reference sensor output, both physically separated.

Typically, at least three test points are required to establish the sensor parameters, generally low, medium and high on the scale of the instrument. This translates to 10%, 50% and 90% of the sensor’s range [4]. As part of the NIST Standard for traceability, these test points must be documented. Another reason for documenting these results is for future calibrations to use the same test points to allow the technician to observe “the magnitude and direction of any changes with each new calibration” [4].

These sensor readings are then transmitted using hand held radio communications between the two technicians, as seen in Figure 2. After the two sets of data have been collected, they are then plotted for comparison, where calibration constants are derived from the plot. The calibration constants are then applied on the sensor’s signal conditioner. The calibration process then repeats itself until sensor readings and reference sensor readings come within an acceptable tolerance [1]. If highly non-linear behavior is observed on the sensor, calibration may not be able to correct the sensor readings, and a repair or replacement has to be performed.

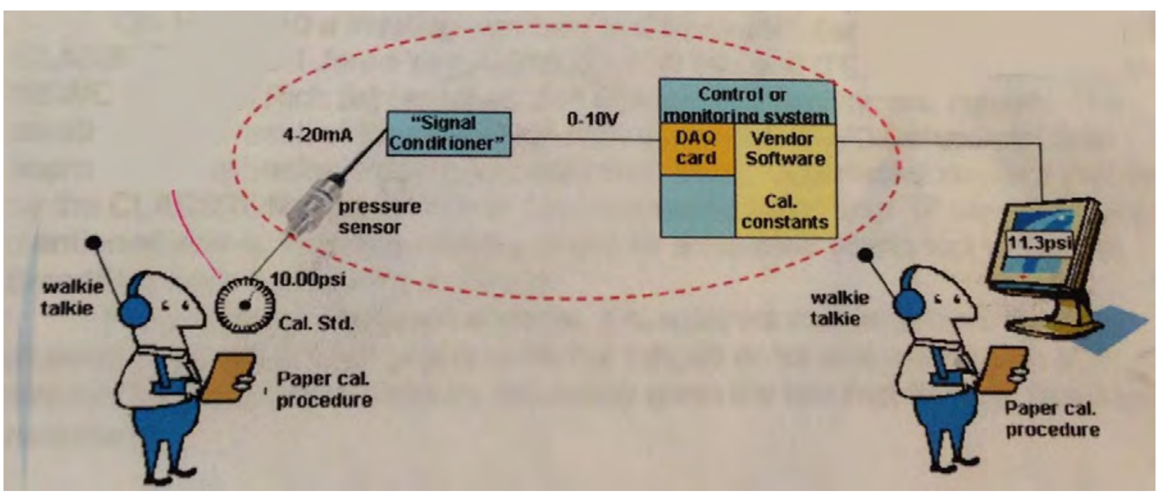

Figure 2. Current calibration procedure, from [5].

C. RELATED WORK

Previous work on improving the efficiency of the sensor calibration process has been conducted by several students at the Naval Postgraduate School.

Steven Joseph Perchalski and Eusebio Pedeo da Silva focused on developing a closed loop calibration procedure of a sensor using a tablet. The sensor readings and calibration commands are transmitted via wireless standards like IEEE 802.11b and Bluetooth. The developed LabVIEW programs on the tablet allowed the technician to perform sensor calibrations by viewing the sensor and the reference sensor readings on a single window. The technician is able to input a range of test points to the calibration software, which automatically computes the new calibration constants using a least-squares fitting method. The program then stores the new constants by updating the sensor's RAM or EEPROM. This closed-loop calibration process enabled a significant reduction in time and the number of personnel required to conduct the maintenance; however, the range of transmission was not established [6, 7].

Chimi Zacot's work focused on developing a wireless sensor network utilizing IEEE 802.14.4 Zigbee technology. Feasibility studies like range, power and reliability were studied before developing a prototype pressure sensor to demonstrate the technology in a shipboard setting. The developed prototype pressure sensor is a Zigbee enabled sensor that is able to transmit its measured readings to various Zigbee enabled stations regardless of their location onboard, reducing the requirement for manning. The motivation of transmitting using Zigbee is due to it being wireless, which brings benefits in weight, space and cost from cabling. In addition, it has low power consumption; however it is intended for low bandwidth applications [8].

Charles Khang Le's work focused on automating the calibration process and allowing technicians to initiate the calibration of sensors via the world-wide-web. Computers are interfaced to the shipboard's local area network (LAN) to collect sensor readings and receive calibration commands. The only work required to be performed by the technicians is to initiate the sensor calibration process via the world-wide-web, should they observe an irregularity in the sensor readings [9].

D. THESIS OUTLINE

The first chapter is the introduction to the thesis, while the problem statement and the proposed concept of operation is in the second chapter. The hardware components, their functions and configurations are the focus of the third chapter. The experimental setup and results that were collected are described in the fourth chapter. Finally, the conclusion and recommendations for future research are contained in the fifth chapter.

II. PROBLEM STATEMENT AND CONCEPT OF OPERATION

A. PROBLEM STATEMENT

As mentioned in the introduction, shipboard sensors play an important role in indicating the health of the ship's machinery. DDG ships have many sensors that require periodic calibration to ensure data integrity. The calibration of these sensors requires at least two technicians due to the physical separation between the system console and the reference sensor instruments readout, which is at least a deck away.

A technician is required to be at the system console to read the sensor output as the readings are not available at the location where the sensor is installed. The design of the ship might also pose a constraint for laying cables to transmit data from the system console to the location of the reference sensor. The current calibration procedure uses a primitive method, which is for the technician to read the display on the system console and transmit the readings to another technician via hand-held communication devices like walkie-talkies.

This research work was conducted to establish the feasibility of COTS components to reduce the man-hour requirements for the calibration of sensors, without using the shipboard LAN, taking into account the layout of the ship and its security constraints.

B. CONCEPT OF OPERATION

The approach described in this section uses COTS components to wirelessly transmit the sensor output that appears on the system console to the technician located at the reference sensor instruments readout without using the shipboard LAN. This eliminates the need for a technician to be stationed at the system console. The technician stationed at the reference sensor instruments readout will be able to compare the readings for the calibration.

The readings are transmitted wirelessly and not by laying cables. An independent, temporary wireless network is setup as opposed to using the shipboard's LAN, so as not to threaten the shipboard's network security.

With the current technology, COTS products are available to implement the aforementioned concept of operation. The display from the system console can be transmitted to a LAN via a Keyboard Video and Mouse (KVM) switch. This non-invasive method of viewing the system console does not threaten the U.S. Navy's security concerns. The LAN output on the KVM allows it to interface to 802.11 routers forming part of the temporary wireless network created for the calibration of sensors. The system console image can then be transmitted wirelessly via repeaters to the technician stationed at the reference sensor instruments readout.

The success of this concept of operation is dependent on the range that can be achieved, that is, the distances between repeaters and the number of repeaters that must be included in the network. The experiments designed in this thesis take into account the layout of the ships.

III. HARDWARE DESCRIPTION AND SETUP

A. HARDWARE SETUP

The hardware components utilized to prove the concept of operations described in Chapter II are shown in Figure 3. The setup consists of a desktop computer, a KVM switch, a router, a wireless access point (AP), repeaters, and a tablet. Each component and its role in the overall calibration system are described below.

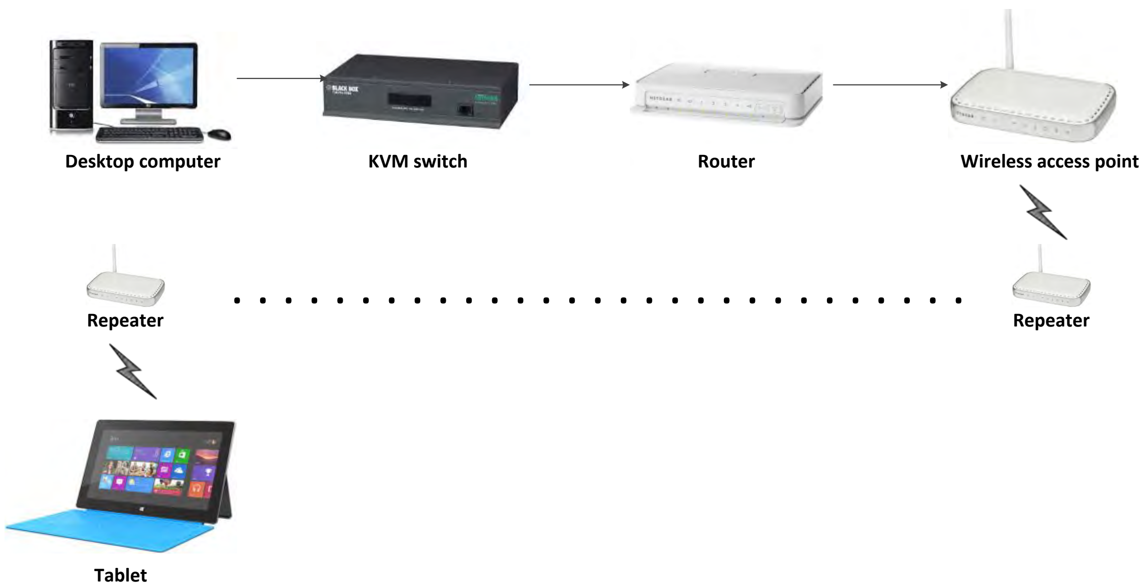

Figure 3. Hardware setup.

B. DESKTOP COMPUTER

The desktop computer emulates the MCS system console. A monitor, keyboard and mouse are connected to it. The desktop computer runs a LabVIEW program shown in Figure 4. The LabVIEW program simulates sensors and machinery values with values updated at a rate of 10 Hz.

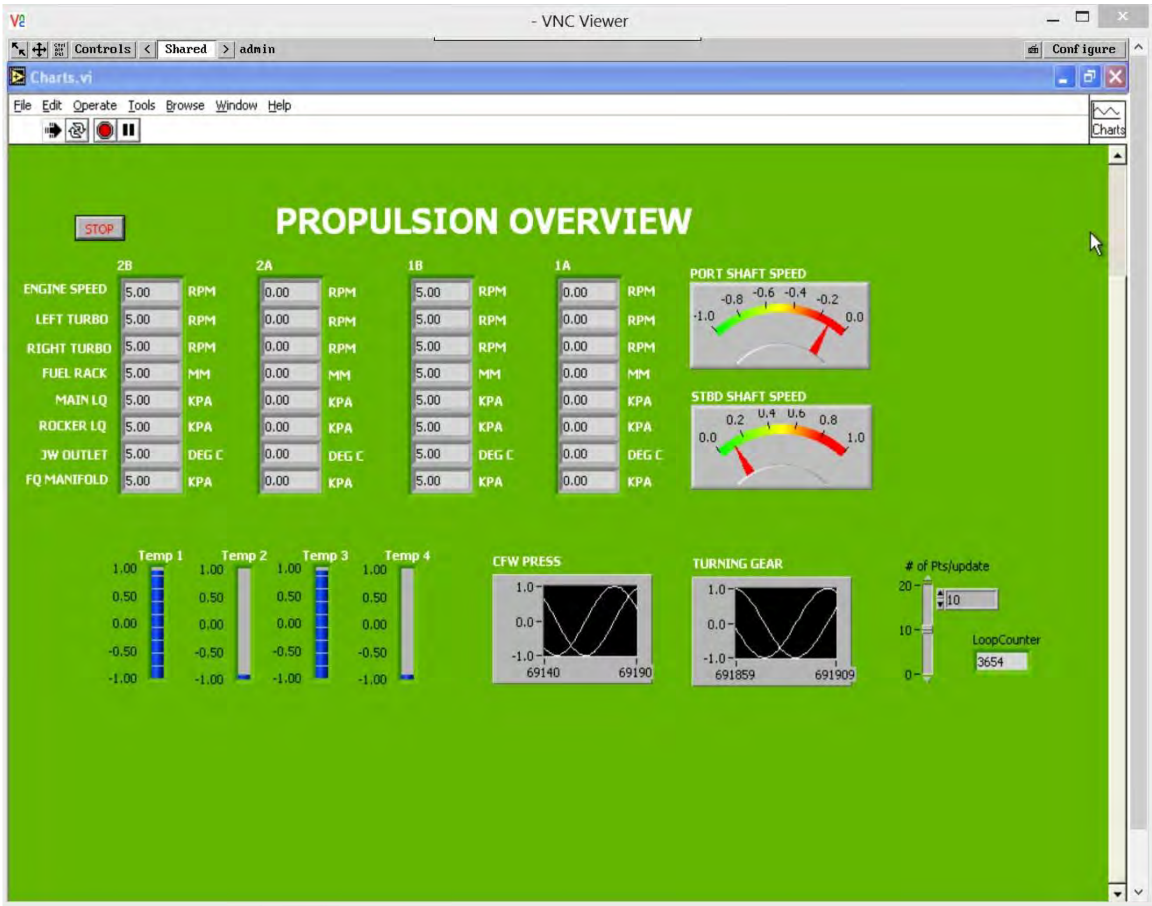

Figure 4. LabVIEW program on desktop computer to emulate the MCS system console.

C. KEYBOARD VIDEO AND MOUSE (KVM) SWITCH

A ServSwitch Wizard IP Plus KVM switch is used to allow remote access of the desktop computer display via an Internet Protocol (IP) network connection [10]. The KVM switch contains an embedded Virtual Network Computing (VNC) server software, which allows devices installed with the VNC client software to gain remote access of the desktop computer connected to the KVM switch. The VNC system uses the Remote Frame Buffer (RFB) protocol for remote access to graphical user interfaces, as shown in Figure 5.

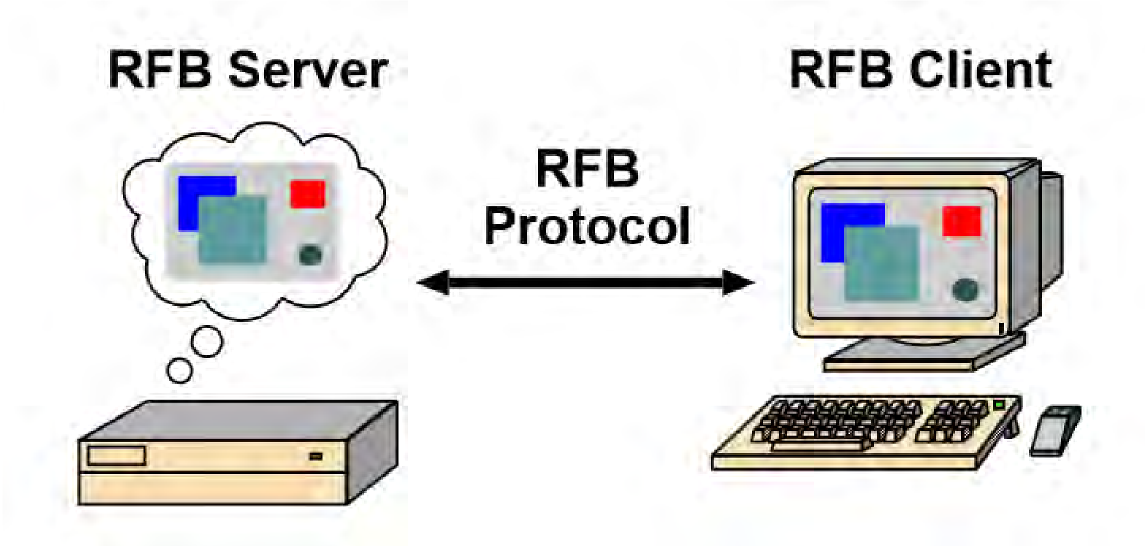

Figure 5. VNC server-client remote access (RFB protocol), from [11].

The RFB protocol, as defined in RFC 6143, works at the frame buffer level, and is applicable to all windowing systems and applications [12]. This includes Windows and Macintosh platforms. Multiple RFB clients are able to connect to the RFB server at the same time [12]. The display protocol works based on putting a rectangle of pixel data at a given *x,y* position on the screen [12]. This implementation might appear to be inefficient, but it allows various encodings for the pixel data, providing a large degree of flexibility [12]. ZRLE, Hextile, Raw, CopyRect, and RRE are encoding types defined for the protocol [12]. On the KVM switch, four encoding options are available: ZRLE, Hextile, Raw and Auto [10]. In our application, the ZRLE option is selected, which is a highly compressed method which has the smallest bandwidth requirement among the options. On the KVM switch, color levels can be selected between Full, Medium, Low and Very Low, since there is a compromise between screen response and color depth when network conditions are poor [10]. In our application, the Low color level is selected, which reduces the host system output to 64 colors. An update is sent from the server to the client only when requested from the client [11]. The slower the client and network, the lower the rate of updates, and the transient states of the frame buffer are ignored, resulting in less network traffic [11].

Another protocol that can be used for remote access is the Remote Desktop Protocol (RDP). It is a proprietary protocol developed by Microsoft for Windows-based applications running on a server [13]. The standard Microsoft Windows does not support multiple user logins via the RDP protocol. The display protocol works by the server using its own video driver to render display output by constructing rendering information into network packets [13].

Comparing the two remote access protocols described above, we found the RFB protocol more suited for applications that are still in the developmental stage due to the flexibility it offers. In terms of operating system's platform selection, the RDP protocol allows remote access only from a Windows-based machine, whereas the RFB protocol works on all windowing systems, not limited to just Windows and Macintosh. This flexibility increases options when choosing the tablet, which has to host a variety of software for other calibration purposes in addition to having the remote access client function to view the server GUI. In terms of accessibility by number of users, the RDP protocol allows only one user to access the server GUI at any one time, whereas the RFB protocol is not limited to one user. This flexibility allows more possibilities for the concept of operations when fine-tuning the calibration process. An advantage of the RDP is its bandwidth efficiency, since it sends instructions and not images of the server's GUI across the network; however, as the concept of operations for the proposed calibration process is still at its preliminary stage, the flexibility of the RFB protocol surpasses the bandwidth advantage offered by the RFB protocol. The KVM switch, embedded with the VNC software based upon the RFB protocol was selected and is further described below.

Another consideration when selecting the KVM switch with an embedded VNC server software is its authentication method. The tablet, installed with the VNC client software, is able to view the Graphical User Interface (GUI) displayed on the monitor of the desktop computer after authenticating connections with the

VNC server, which is embedded on the KVM switch; hence, the calibration setup does not require the desktop computer's user credentials, which may be sensitive information that is of a security concern to the U.S. Navy.

The front view of the KVM switch is shown in Figure 6. It connects to the router to form part of the temporary network for the calibration setup.

Figure 6. KVM switch (front view), after [10].

The back view of the KVM switch is shown in Figure 7. It connects to two Digital Visual Interface (DVI) Connectors. One connects to the monitor and the other to the desktop computer. In this setup, the KVM switch serves as an interface between the desktop computer and the monitor. In a typical setup without the KVM switch, the desktop computer connects to the monitor directly via a DVI interface.

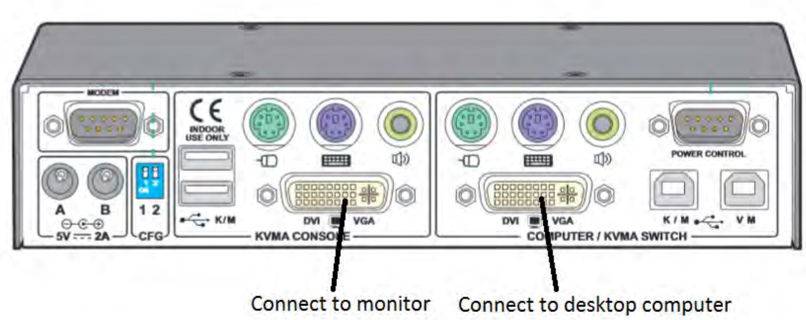

Figure 7. KVM switch (back view), after [10].

D. ROUTER

A Netgear RP614 router is used to create a dedicated Local Area Network (LAN) for the calibration setup. The KVM switch and the wireless AP connect to the router via any two of the LAN ports labelled 1 through 4 in Figure 8.

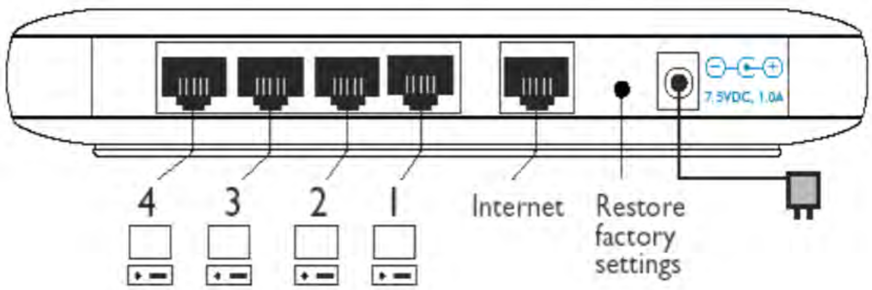

Figure 8. Router (back), after [14].

The router is able to dynamically assign network configuration information, including IP, subnet mask, gateway, and domain name server (DNS) addresses to attached devices that are connected to the same LAN using the Dynamic Host Configuration Protocol (DHCP). The router has to enable its setting to be a DHCP server, as shown in Figure 9.

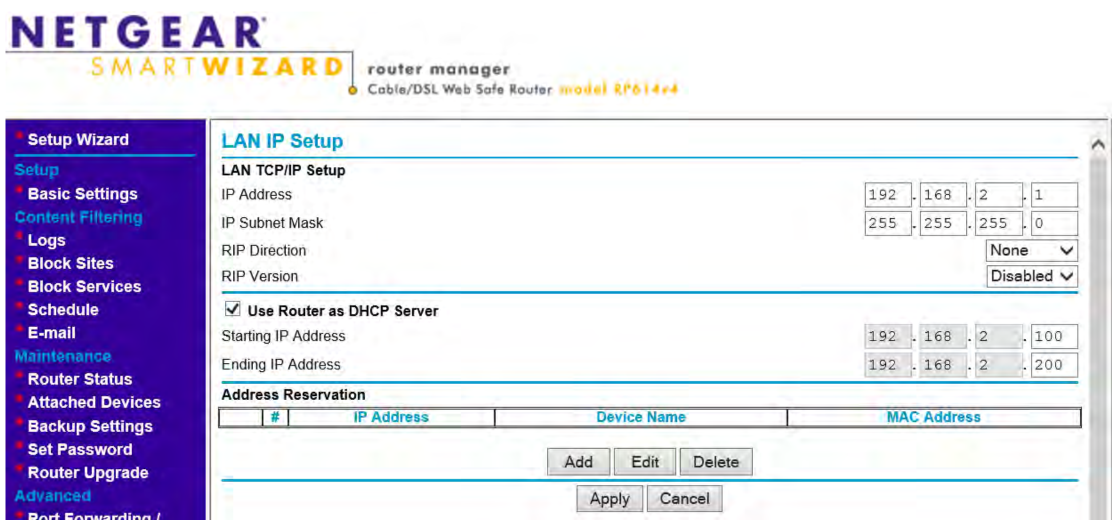

Figure 9. Router setting (DHCP enabled).

E. ACCESS POINT

A Netgear N150 WN604 wireless AP is used to allow wireless devices to connect to the wired LAN. The wireless devices in this network consist of the repeaters and the tablet. The wired devices in this network consist of the KVM switch, router and the tablet. The only physical connection is to the router via one of the LAN ports, labelled 1 to 4 in Figure 10. The wireless settings are shown in Figure 11.

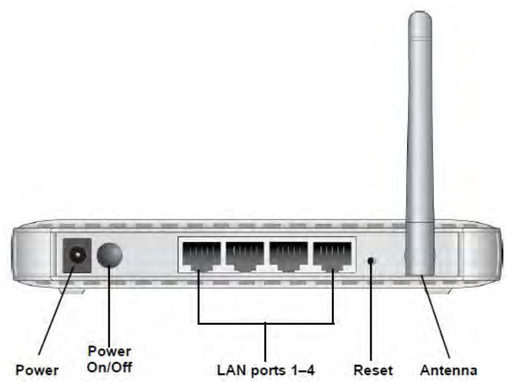

Figure 10. Wireless AP (back), from [15].

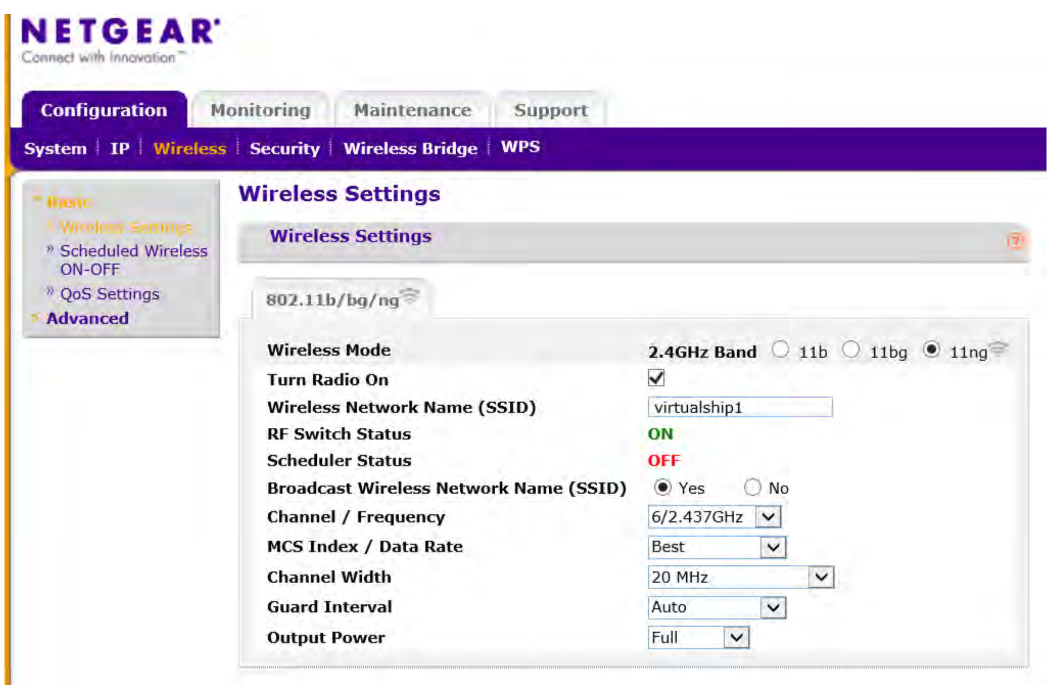

Figure 11. Wireless AP's wireless settings.

The Wireless Mode selected is 11ng, which indicates that it can communicate with 802.11ng, 802.11g, and 802.11b wireless devices [15]. The Channel/Frequency selected is dependent on channel utilization during testing. It is set to the channel with the least traffic. The 802.11 spectrum is 100.0 MHz wide and made up of 11 channels, each centered 5.0 MHz apart [16]; hence, each channel is about 20.0 to 22.0 MHz wide [16]. As shown in Figure 12, channels 1, 6, and 11 are the only three channels that do not overlap [16].

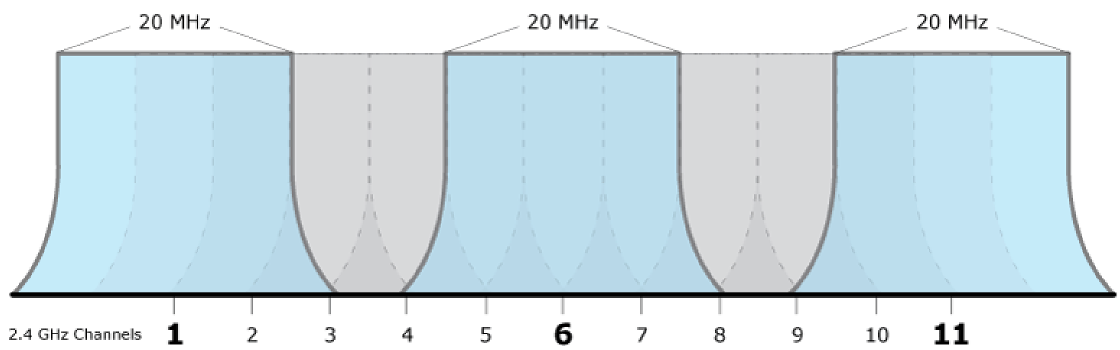

Figure 12. 802.11's frequency width for channels 1, 6 and 11, from [16].

F. REPEATERS

A TP-LINK TL-WR700N 150Mbps Wireless N Router is used to extend the range of the wireless network between the wireless AP and the tablet. It does not have any physical connections since it is a wireless device. It is set up in the Repeater mode, which propagates the wireless network using the same Service Set Identification (SSID) as the wireless AP [17]; hence, multiple repeaters with identical settings can be added into the network.

A repeater receives radio signals from the wireless AP or another repeater and retransmits the message frames without changing the frame contents [18]. The repeaters act as relay points for frames travelling between the wireless AP and the tablet. Adding repeaters into the wireless network extends the range achievable by the wireless network when placed in an optimal position.

A repeater receives and retransmits the frames using the same radio [18]; hence, each repeater reduces the bandwidth that is available to it by at least 50 percent. The speed of the overall wireless network is impacted by the number of repeaters added. When adding repeaters into the network, considerations have to be made in the tradeoff between range and speed.

G. TABLET

A Windows Surface Tablet, as shown in Figure 13, is a portable hand-held tablet that has the specifications of a laptop. It measures 11.5 inches by 7.93 inches by 0.36 inches with a 12.0 inch screen and weighs 800 grams [19]. It is also free of peripheral connections as it comes with a built-in battery and has a touch-screen surface [19], making it convenient for field deployment. It runs on the Windows operating system [19], which facilitates software development and testing since most programming platforms and testing kits are compatible with the Windows operating system.

Figure 13. A portable hand-held tablet - Windows Surface Tablet, from [20].

The tablet is installed with the RealVNC client software, the Wireshark software, and the WifiInfoView software.

1. VNC Client Software

As mentioned in an earlier section, the KVM switch is embedded with a VNC server software. The tablet, when installed with the VNC client software, must be able to gain remote access of the desktop computer which is connected to the KVM switch; hence, the GUI from the desktop computer can be viewed on the tablet.

2. Wireshark Software

The Wireshark is a free and open-source packet analyzer software [21]. It is typically used for network troubleshooting and analysis [21]. It is able to read and capture live data from various types of network, including 802.11 traffic [21].

A sample capture on Wireshark is shown in Figure 14. Wireshark is able to capture all traffic between the desktop computer (192.168.2.100) and the KVM switch (192.168.2.93). It displays the timestamp, source and destination IP address, protocol, packet length, and additional information on the packet.

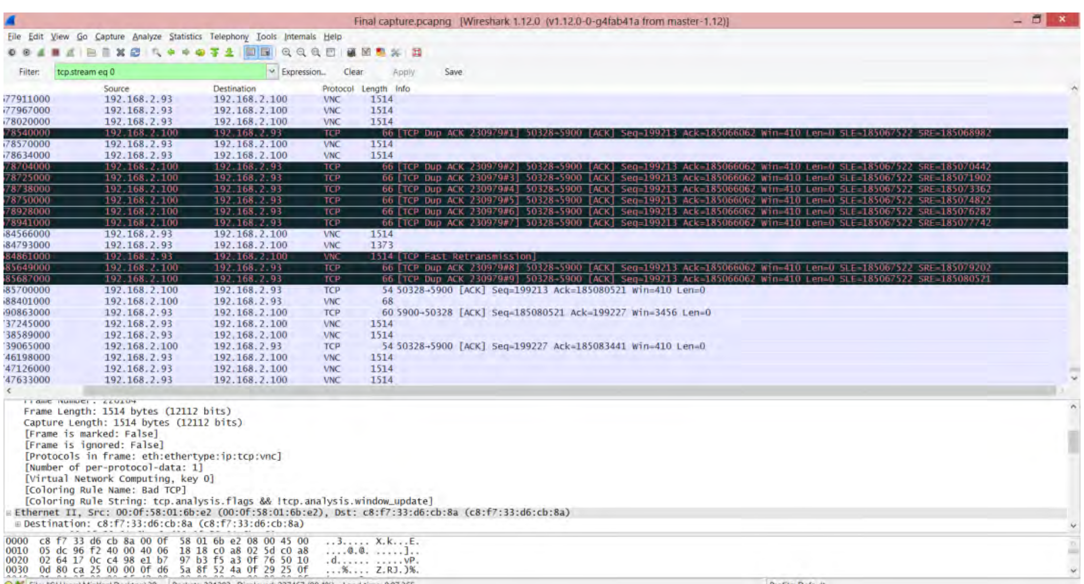

Figure 14. A sample capture on Wireshark.

Majority of the packets captured are classified under the VNC and Transport Control Protocol (TCP) protocol, as VNC uses TCP as its transport layer protocol [12].

While capturing data, Wireshark is able to provide a graphical view of the instantaneous throughput of the network, as shown in Figure 15. The instantaneous throughput provides insights on the number of successful bits/bytes/packets that are delivered over the wireless network. Observing this parameter provides a quantitative measure of how much data has reached the tablet after losses in the wireless network.

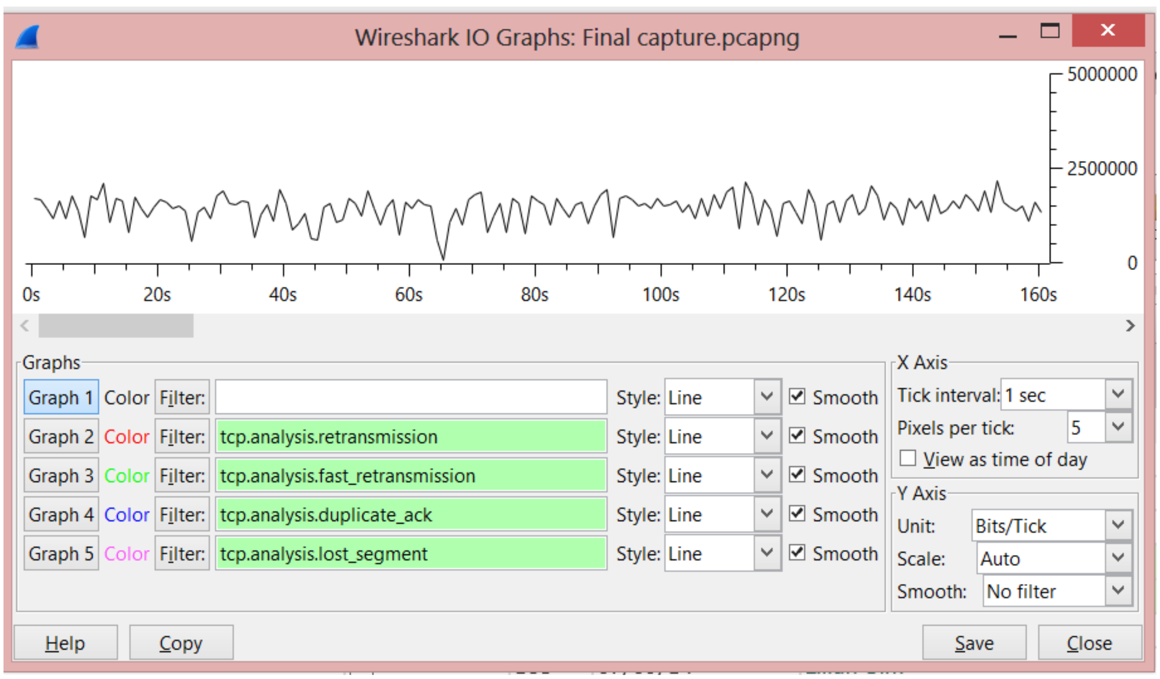

Figure 15. Wireshark IO graph showing throughput of a network.

During the post analysis, filters can be added to gain clarity of the network conditions by observing the TCP messages. Some of the filters present parameters that are generated by TCP when performing congestion control. TCP performs congestion control in the network, as defined in RFC 2581, to mitigate the effects of packet losses and delays [22].

In a TCP session, a 32-bit sequence number is used to keep track of the amount of data sent. This sequence number is included on each transmitted packet and acknowledged by the receiver with an acknowledgement (ACK) number. The sender then bases on the receipt of this ACK as a confirmation that the transmitted data was received successfully [22].

Certain parameters are captured when the expected ACK is not received. They include the number of lost segments, number of duplicate ACKs, number of retransmissions, and number of fast retransmissions.

The number of lost segments is logged by Wireshark when the receiver receives a packet with a sequence number greater than the next expected sequence number. This might not indicate a network problem since the packets could have arrived in an out-of-ordered segment; however, it could also suggest packet loss, which can lead to duplicate ACKs, retransmissions and fast retransmissions.

The number of duplicate ACKs is logged by Wireshark when acknowledgements of the same packet are received more than one time. Duplicate ACKs are typically sent by the receiver when the receiver receives a packet whose sequence number is larger than what it expects. Similar to the “lost segments” parameter, this might not indicate a network problem since the packets could have arrived in an out-of-order segment; however, it could also imply a packet loss, whereby all subsequent received packets trigger a duplicate ACK.

The number of retransmissions is logged by Wireshark when the sender has to retransmit a packet after the expiration of the ACK it was expecting from the receiver. After sending a packet, the TCP sets up its own timer for the sent packet. The timer is known as the retransmission timeout (RTO). If the sender does not receive an ACK for the sent packet within the RTO, TCP triggers a retransmission for the same packet.

The number of fast retransmissions is logged by Wireshark when the sender retransmits a packet before the RTO period is up. When the sender receives three duplicate ACKs, it interprets that the duplicate ACKs are not generated due to the reordering of segments but due to a loss of packet; hence, the sender retransmits the packet before the RTO period is up.

3. WifiInfoView Software

The WifiInfoView scans the wireless networks that are detected by the tablet and displays various parameters as shown in Figure 16 [23]. The parameters presented by WifiInfoView provides insights on which channels to avoid using in order to minimize interference with existing wireless networks.

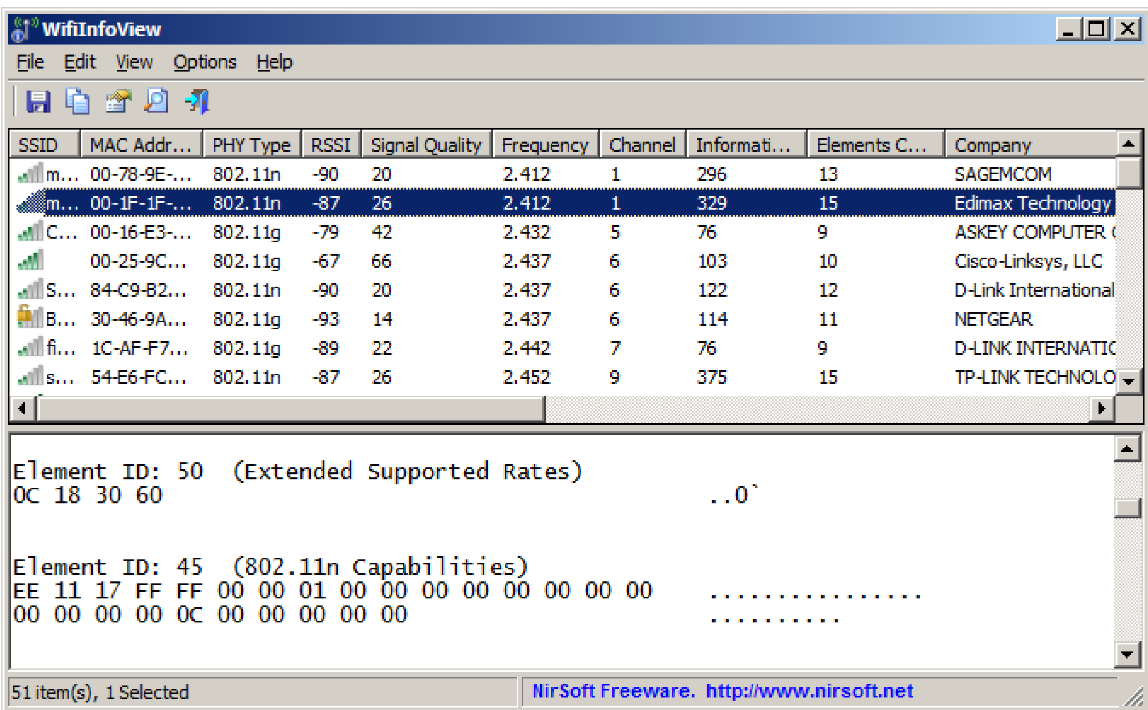

Figure 16. Parameters shown in detected wireless network, from [23].

The channel used by each wireless network can be observed from the Channel column. The Received Signal Strength Indicator (RSSI) value provides a measurement of the power present in the received signal from the wireless network. A larger RSSI value indicates a stronger received signal.

As explained in the wireless AP section, the AP should be assigned a channel that minimizes channel interference, which is typically channel 1, 6 and 11; however, not all networks follow the unspoken rule of using channel 1, 6 or 11. With these parameters as references, the AP should be assigned a channel that is not utilized and is not affected by other channels, using the frequency occupancy graph shown in Figure 12 as a guideline. If that is not practical, the AP should avoid channels with networks that have large RSSI values.

IV. EXPERIMENTAL SETUP AND RESULTS

All the hardware to connect to the MCS is installed in a suitcase, as shown in Figure 17, for portability. The suitcase measures 23.5 inches by 14.5 inches by 8 inches and can be carried by one technician.

Figure 17. Portable suitcase containing hardware to emulate MCS.

Upon deciding the location to emulate the MCS, the hardware in the suitcase, which consists of the compact desktop computer, KVM switch, router and wireless AP, is powered up by AC power. After the desktop computer is powered up, it automatically launches the LabVIEW program. The wireless network consisting of the KVM switch, router and wireless AP is also set up after the power is turned on.

Subsequently, several steps are conducted using the tablet to complete the setup:

- Activate WifiInfoView to check the channel number and RSSI of the existing wireless networks and use this information to decide on the channel number on which to transmit.
- Connect to the wireless network with SSID “virtualship1.”
- After connection is established, open a web browser, and key in the IP address of the wireless AP - http://192.168.2.99/index.php to select the desired channel.
- Activate VNCViewer to connect to the KVM switch (192.168.2.93), with a required password. The GUI on the desktop computer is transmitted to the tablet via the wireless network.
- Activate Wireshark to capture the packets for this wireless network.

After the above steps, the setup is complete. The tablet, which serves as the hand-held portable device used by the technician manning the reference sensor and conducting the sensor calibration, is ready to capture parameters of the wireless network in various locations. The selected locations, as described below, aim to emulate the layout of a ship.

A. BASELINE MEASUREMENT – WIRED

A baseline measurement is done with the tablet connected directly to the router via a LAN cable to collect the statistics of the network conditions when no free-space loss is present. The measurement captures the throughput required to transmit the GUI on the desktop computer to the tablet. It also captures the TCP parameters such as lost segments, duplicate ACKs, retransmissions and fast retransmission. The measured throughput averages about 200,000 bytes per second, as shown in Figure 18. There were no lost segments, duplicate ACKs, retransmissions and fast retransmissions.

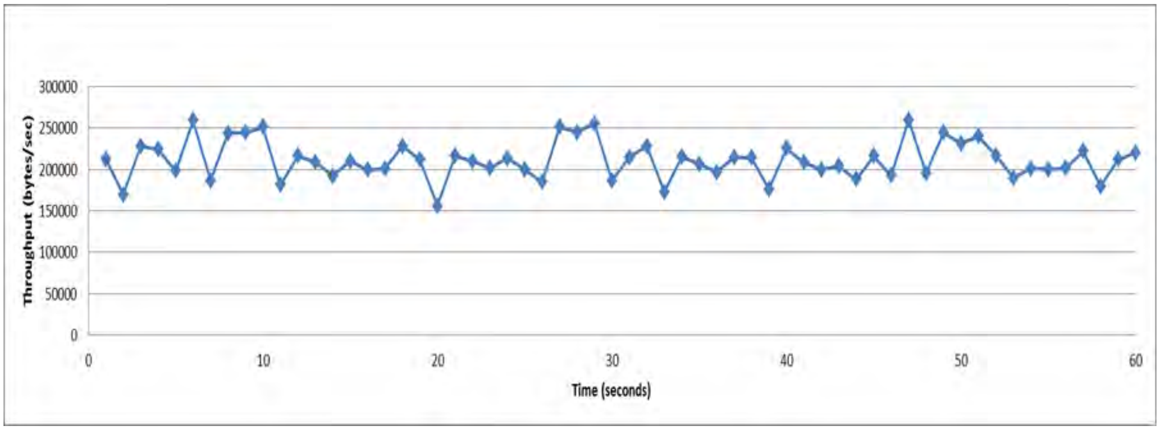

Figure 18. Throughput for wired test.

B. ACROSS THE HALLWAY – CLEAR LINE-OF-SIGHT (LOS)

An experiment was conducted across the hallway at Level Five of Spanagel Hall in Naval Postgraduate School. The suitcase is setup at one end of the hallway, while the tablet is placed beside the wireless AP and at the end of the hallway to collect statistics of the network conditions.

In this setup, there is a clear LOS between the wireless AP and the tablet. This emulates the deck of the ship where the MCS system console is located. There is typically a clear LOS until the stairways leading to other decks of the ship.

1. Zero Meters between Tablet and Wireless AP

When the tablet is placed beside the AP, i.e., zero meters away from the wireless AP, the throughput averages at about 200,000 bytes per second, as shown in Figure 19.

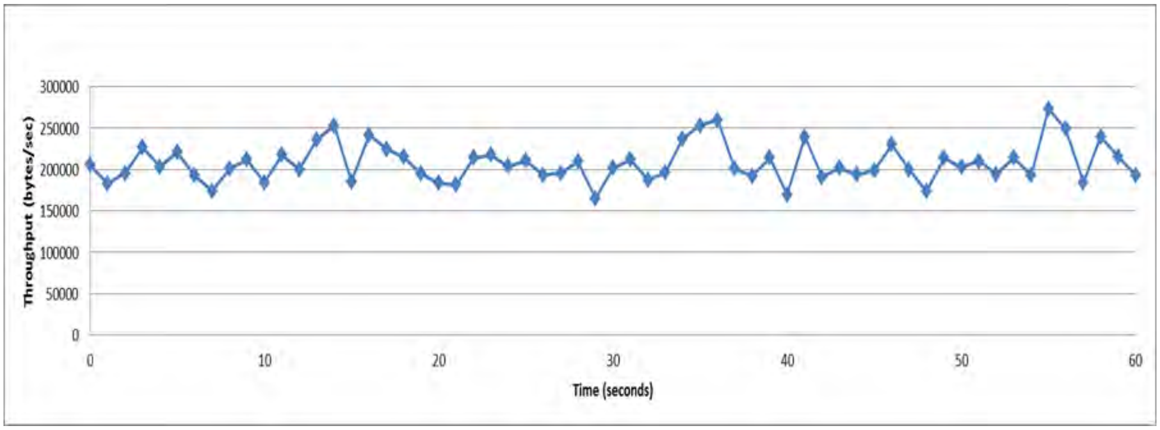

Figure 19. Throughput for hallway test – zero meters from wireless AP.

TCP parameters, such as lost segments, duplicate ACKs, retransmissions and fast retransmissions, are shown in Figure 20. It is observed that there is one instance, at 45 s, where there is a lost segment and duplicate ACKs, which resulted in retransmission and fast retransmission of the packet.

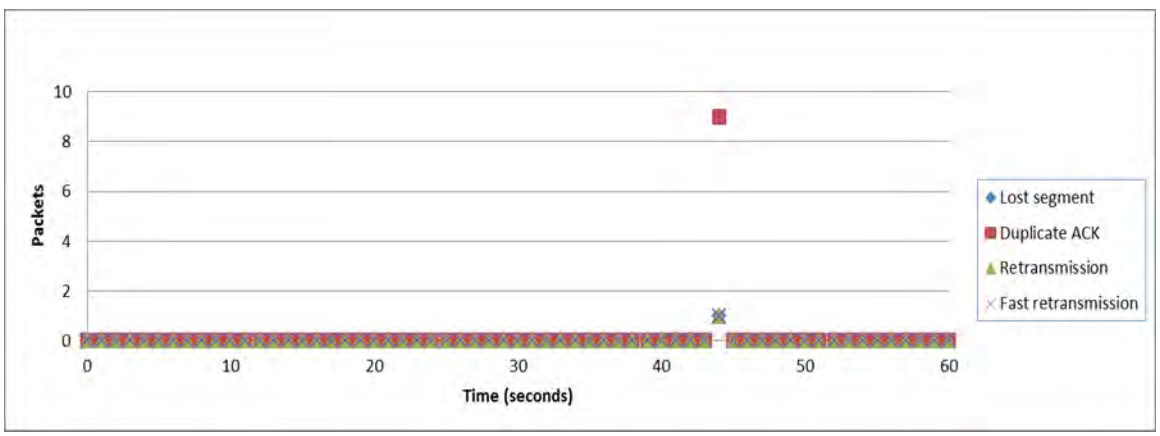

Figure 20. TCP parameters – zero meters between tablet and wireless AP.

2. 100 m between Tablet and Wireless AP

When the tablet is placed 100 m away from the wireless AP, the throughput averages about 200,000 bytes per second, as shown in Figure 21.

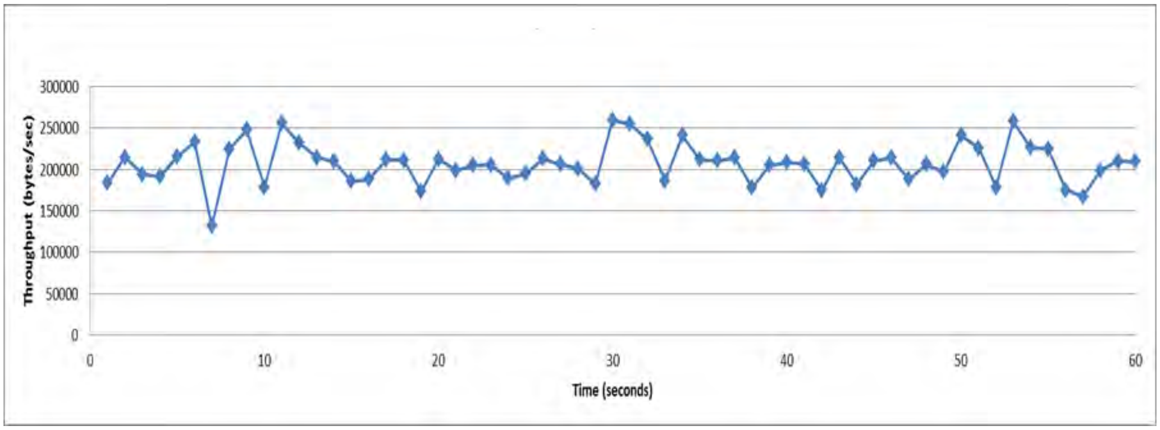

Figure 21. Throughput for hallway test – 100 m between tablet and AP.

TCP parameters, such as lost segments, duplicate ACKs, retransmissions and fast retransmissions are shown in Figure 22. It is observed that there are two instances, at 7 s and 41 s, where there are lost segments and duplicate ACKs, which resulted in retransmission of the packets.

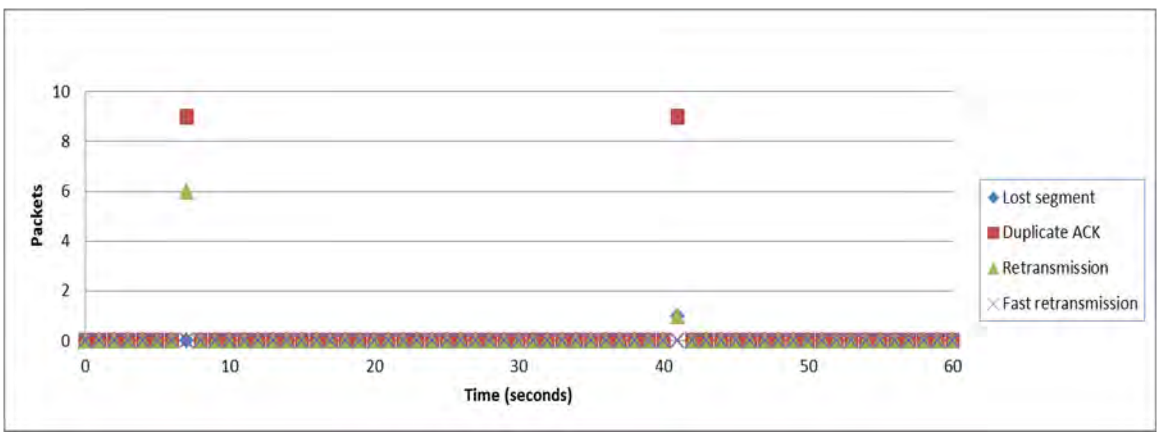

Figure 22. TCP parameters – 100 m between tablet and AP.

As the throughput and TCP parameters at 0.0 m and 100 m are very similar, there is no value in adding a repeater to boost the wireless signal.

C. ALONG THE STAIRWAYS – NO LOS

Another experiment was conducted in the stairways at Spanagel Hall in Naval Postgraduate School. The suitcase is set up at Level 4.5, which is in the stairway between the 4th and 5th floor. The tablet is placed at Level 4, Level 3.5, Level 3, Level 2.5, Level 2, Level 1.5 and Level 1 to collect statistics of the network conditions at varying distances from the wireless AP.

In this setup, there is no clear LOS between the wireless AP and the tablet. This emulates the flight of stairs in the ship when moving from the deck where the MCS system console is located to the deck where the sensor is installed.

In addition, the following configurations were conducted to establish the impact of repeaters on the range of the network:

- No repeaters
- One repeater at Level 1.5
- One repeater at Level 2.5
- One repeater at Level 3.5
- Two repeaters – One at Level 2.5 and one at Level 1.5
- Two repeaters – One at Level 3.5 and one at Level 1.5
- Two repeaters – One at Level 3.5 and one at Level 2.5
- Three repeaters – One at Level 3.5, one at Level 2.5 and one at Level 1.5.

Due to the constraint of having only five levels in Spanagel Hall, a maximum of three repeaters were used for the experiment.

The throughput graphs in this section show the measured throughput in blue and the average throughput of 200,000 bytes per second in red, established in the baseline measurement in Section IV.A.

1. Readings Measured at Level 4

Measurements were collected using the tablet at Level 4 for various configurations of repeaters. Measurements were collected at Level 4 even though it is intuitive that the repeaters will have no impact on the network range since the tablet is very near the wireless AP; however, it was collected and is presented for completeness.

The throughput measured at Level 4, when no repeaters were used, is shown in Figure 23 by the blue line. It hovered about the average baseline value of 200,000 bytes per second as shown by the red line. Visually, there was no lag observed on the tablet.

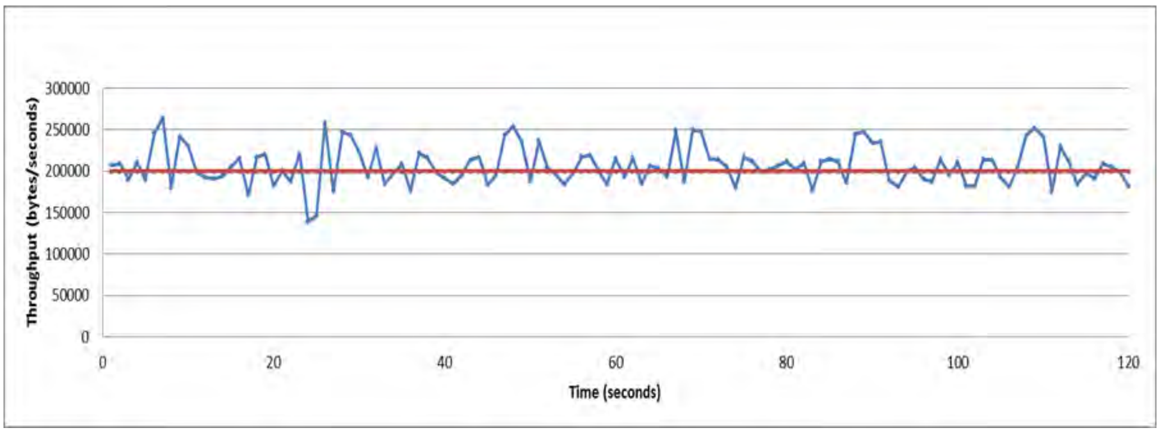

Figure 23. Throughput measured at Level 4 – no repeaters.

The throughput measured at Level 4, when one repeater was placed at Level 1.5, is shown in Figure 24 by the blue line. It hovered about the average baseline value of 200,000 bytes per second as shown by the red line. Visually, there was no lag observed on the tablet.

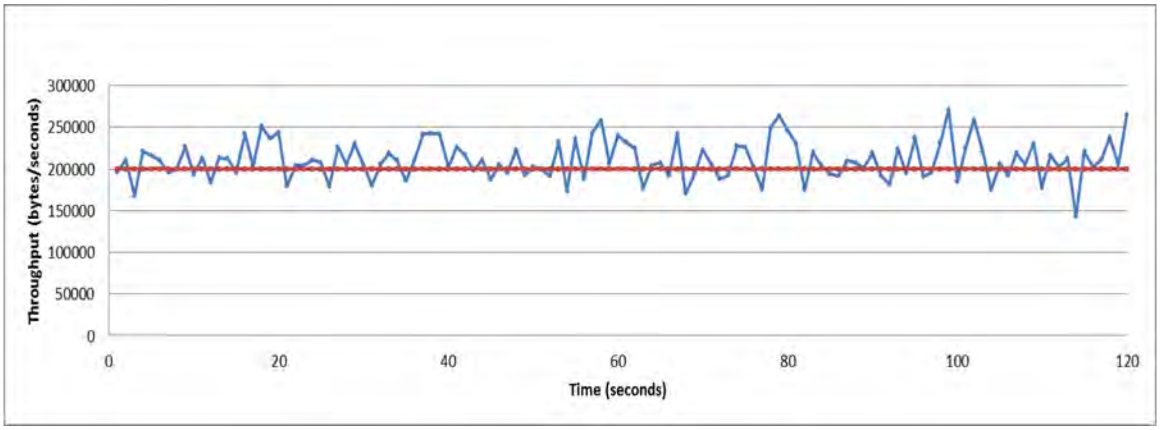

Figure 24. Throughput measured at Level 4 – one repeater at Level 1.5.

The throughput measured at Level 4, when one repeater was placed at Level 2.5, is shown in Figure 25 by the blue line. It hovered about the average baseline value of 200,000 bytes per second as shown by the red line. Visually, there was no lag observed on the tablet.

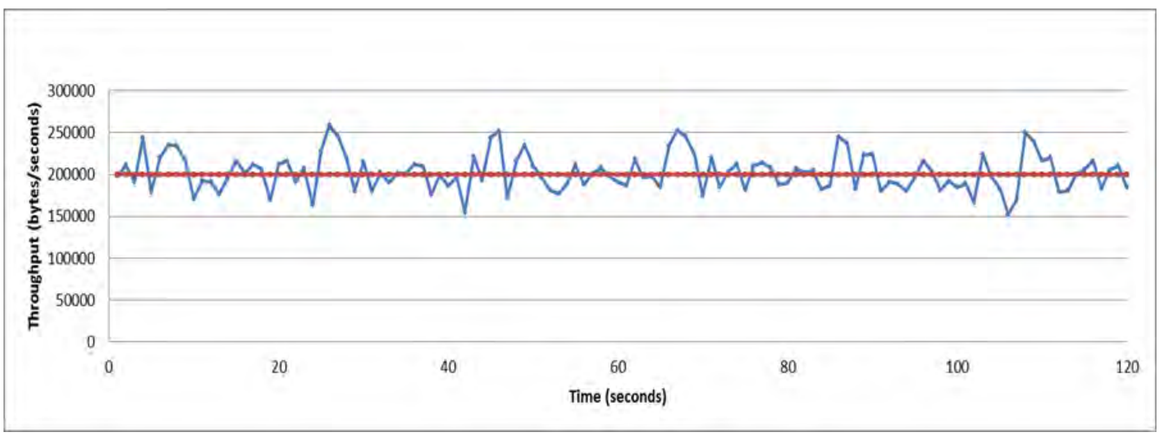

Figure 25. Throughput measured at Level 4 – one repeater at Level 2.5.

The throughput measured at Level 4, when one repeater was placed at Level 3.5, is shown in Figure 26 by the blue line. It hovered about the average baseline value of 200,000 bytes per second as shown by the red line. Visually, there was no lag observed on the tablet.

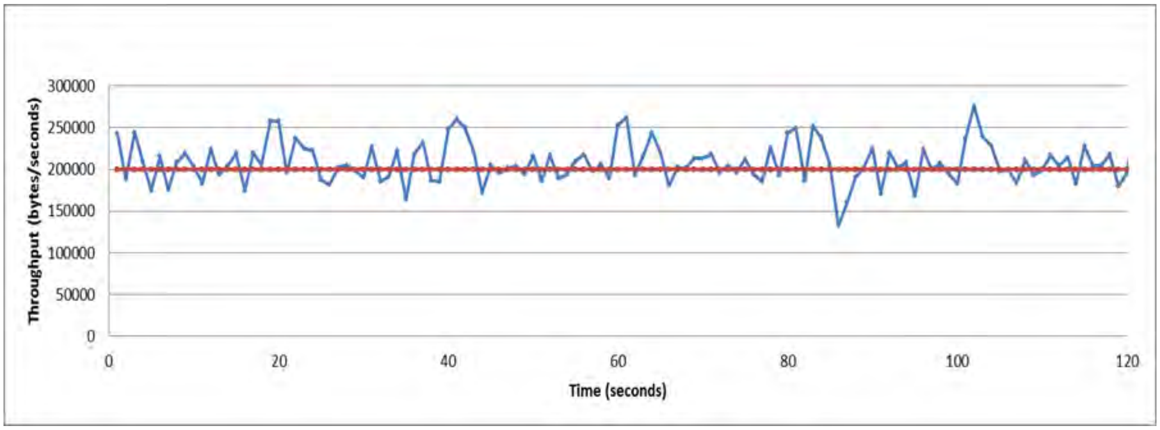

Figure 26. Throughput measured at Level 4 – one repeater at Level 3.5.

The throughput measured at Level 4, when one repeater was placed at Level 2.5 and one repeater was placed at Level 1.5, is shown in Figure 27 by the blue line. It hovered about the average baseline value of 200,000 bytes per second as shown by the red line. Visually, there was no lag observed on the tablet.

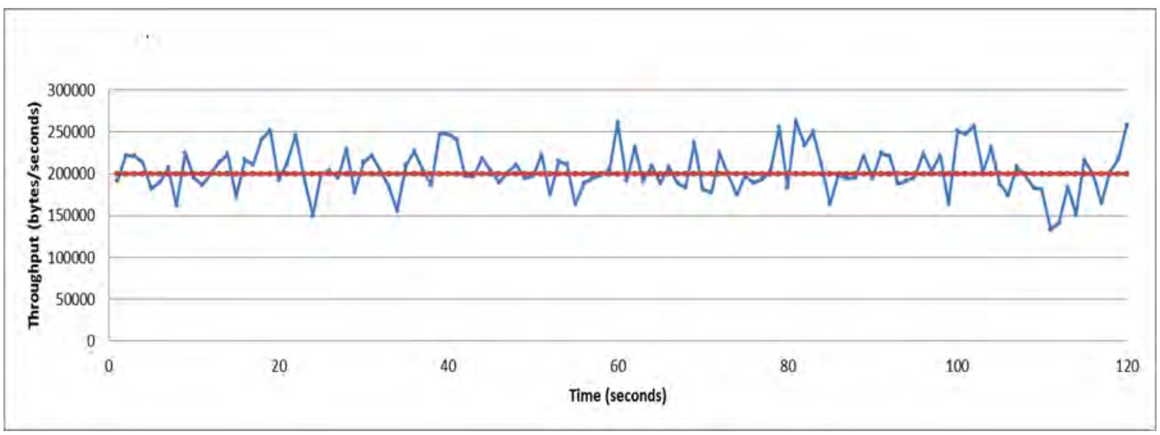

Figure 27. Throughput measured at Level 4 – one repeater at Level 2.5, one repeater at Level 1.5.

The throughput measured at Level 4, when one repeater was placed at Level 3.5 and one repeater was placed at Level 1.5, is shown in Figure 28 by the blue line. It hovered about the average baseline value of 200,000 bytes per second as shown by the red line. There were two instances of dips below 100,000 bytes per second, which correspond to momentary screen freezes. Overall, visually, there was no lag observed on the tablet.

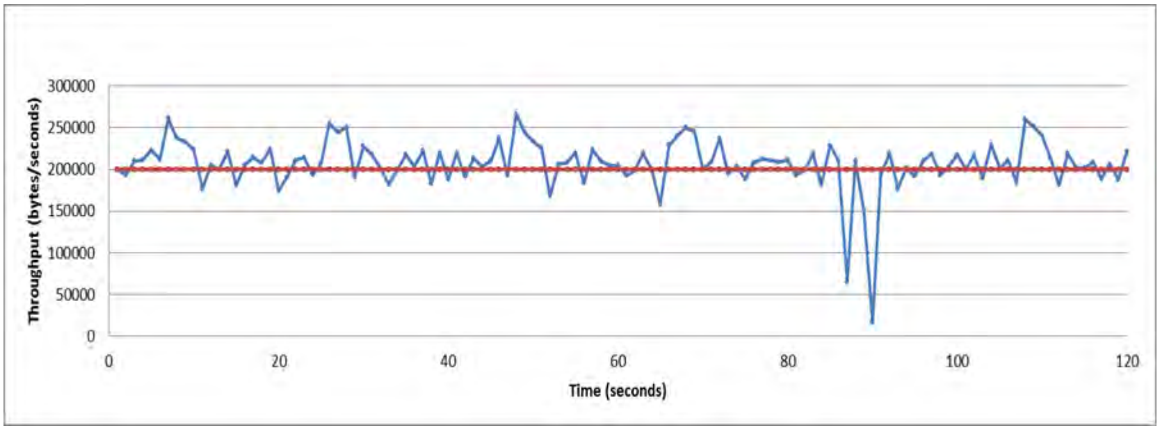

Figure 28. Throughput measured at Level 4 – one repeater at Level 3.5, one repeater at Level 1.5.

The throughput measured at Level 4, when one repeater was placed at Level 3.5 and one repeater was placed at Level 2.5, is shown in Figure 29 by the blue line. It hovered about the average baseline value of 200,000 bytes per second as shown by the red line. There was one instance of dip below 100,000 bytes per second, which correspond to a momentary screen freeze. Overall visually, there was no lag observed on the tablet.

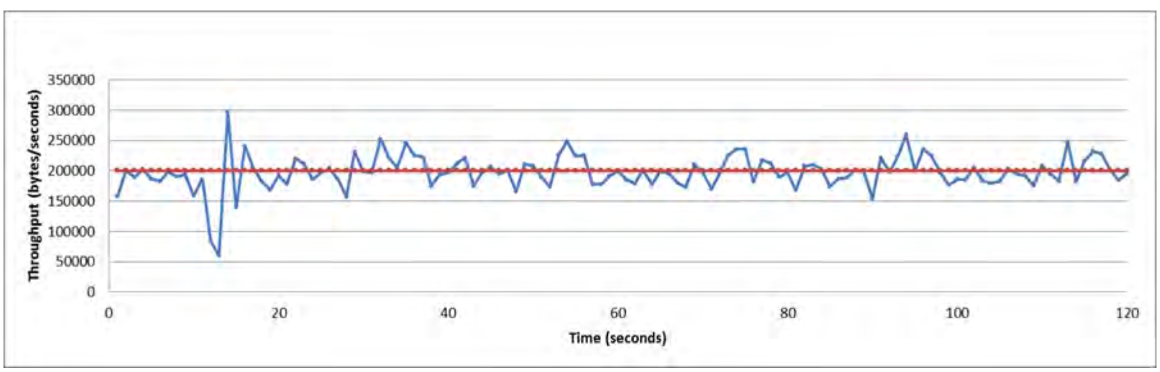

Figure 29. Throughput measured at Level 4 – one repeater at Level 3.5, one repeater at Level 2.5.

The throughput measured at Level 4, when one repeater was placed at Level 3.5, one repeater was placed at Level 2.5, and one repeater was placed at Level 1.5, is shown in Figure 30 by the blue line. It hovered about the average baseline value of 200,000 bytes per second as shown by the red line. Visually, there was no lag observed on the tablet.

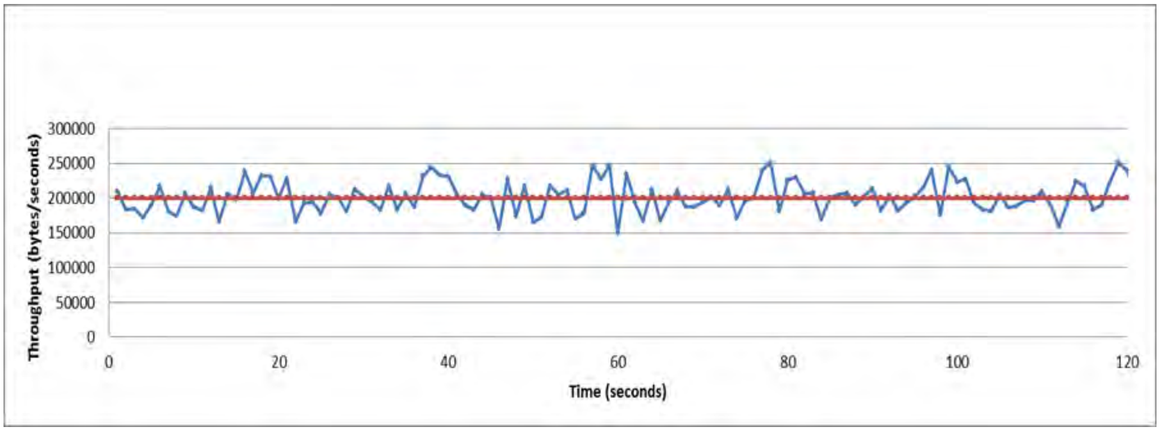

Figure 30. Throughput measured at Level 4 – one repeater at Level 3.5, one repeater at Level 2.5, one repeater at Level 1.5.

There were no obvious differences in the quality of display on the tablet for all configurations of repeaters measured at Level 4.

2. Readings Measured at Level 3.5

Measurements were collected using the tablet at Level 3.5 for various configurations of the repeaters.

Throughput plots similar to those measured at Level 4 are shown in Figure 31 to Figure 37. It is observed that the general trend for the throughput for all configurations measured at Level 3.5 hovered about the average baseline value of 200,000 bytes per second. Visually, there was no lag observed for all configurations. There were no obvious differences in the quality of display on the tablet for all configurations at Level 3.5.

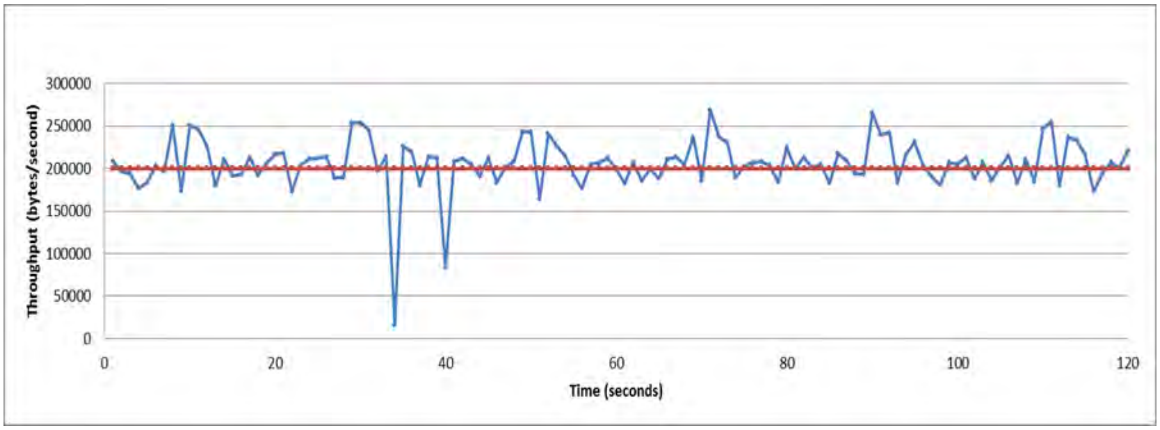

Figure 31. Throughput measured at Level 3.5 – no repeaters.

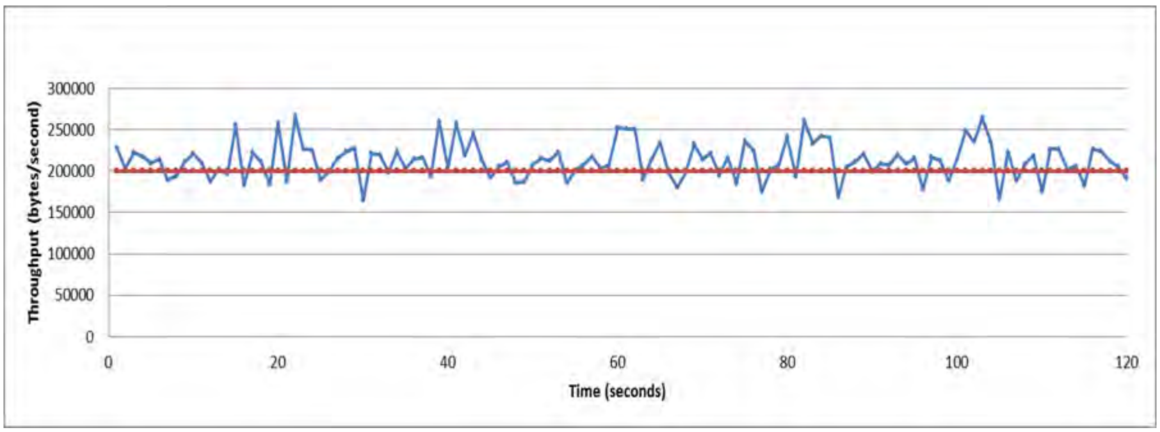

Figure 32. Throughput measured at Level 3.5 – one repeater at Level 1.5.

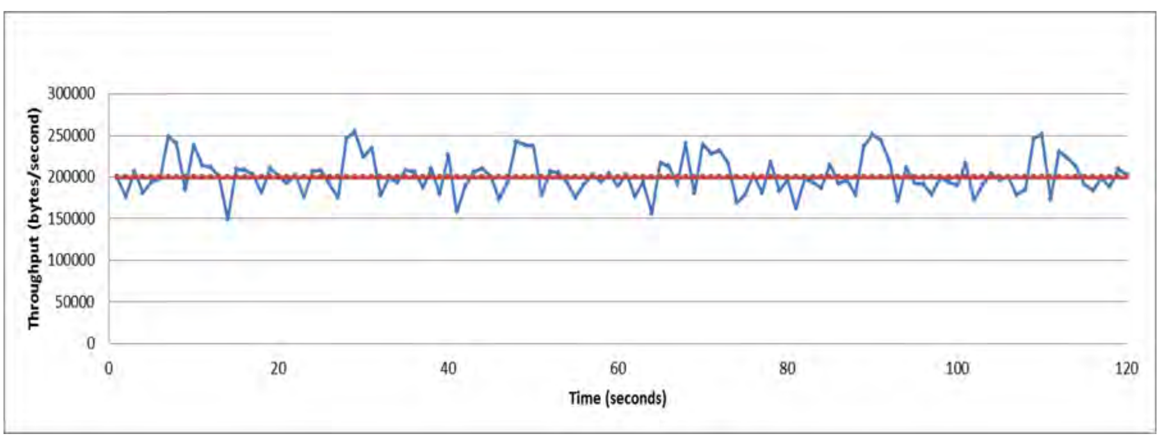

Figure 33. Throughput measured at Level 3.5 – one repeater at Level 2.5.

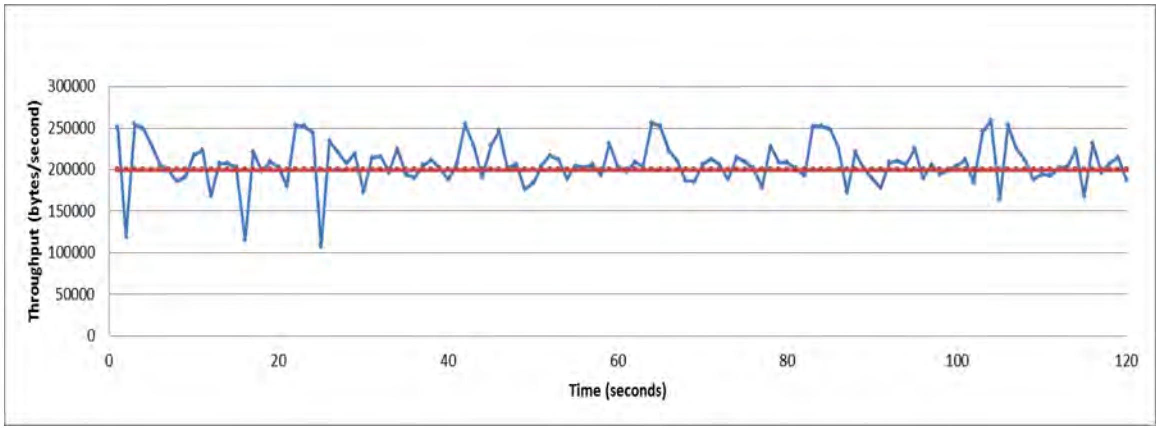

Figure 34. Throughput measured at Level 3.5. – one repeater at Level 3.5.

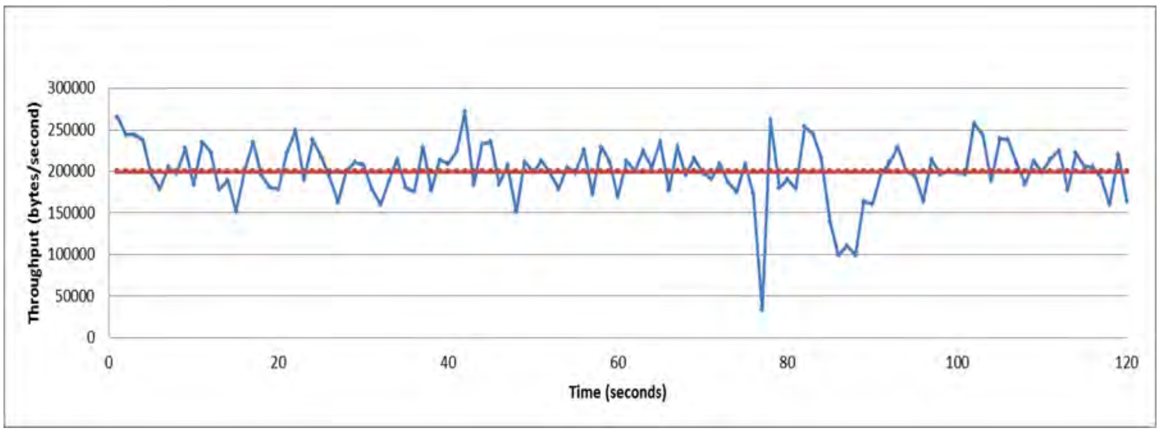

Figure 35. Throughput measured at Level 3.5 – one repeater at Level 2.5, one repeater at Level 1.5.

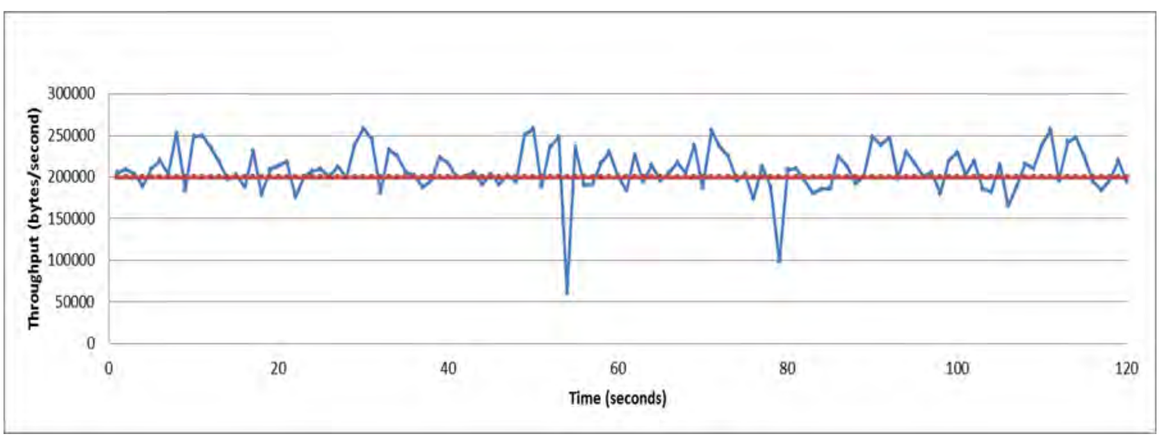

Figure 36. Throughput measured at Level 3.5 – one repeater at Level 3.5, one repeater at Level 1.5.

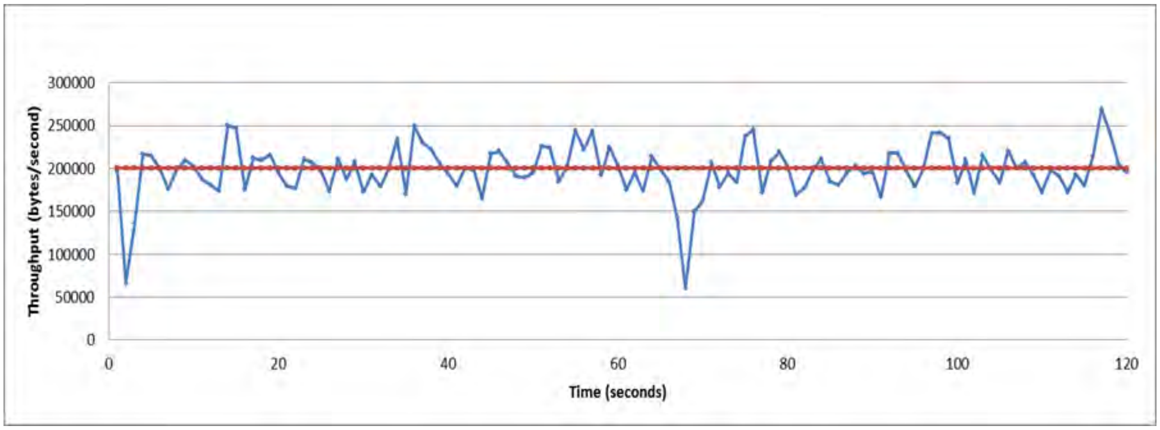

Figure 37. Throughput measured at Level 3.5 – one repeater at Level 3.5, one repeater at Level 2.5.

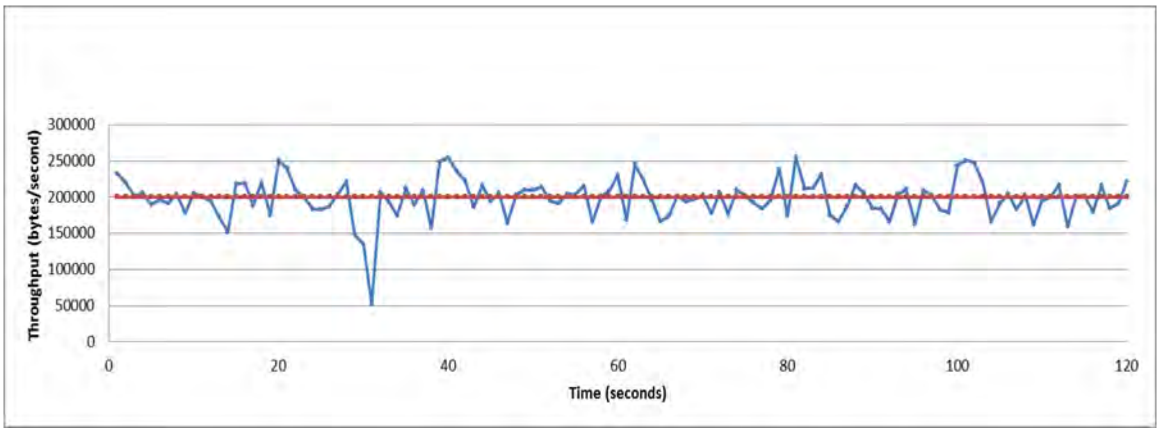

Figure 38. Throughput measured at Level 3.5 – one repeater at Level 3.5, one repeater at Level 2.5, one repeater at Level 1.5.

3. Readings Measured at Level 3

Measurements were collected using the tablet at Level 3 for various configurations of the repeaters.

From Figure 39 to Figure 46, it is seen that the general trend for the throughput for all configurations measured at Level 3 hovered about the average baseline value of 200,000 bytes per second. Visually, there were instances of lag observed for the following configuration:

- One repeater at Level 2.5, one repeater at Level 1.5.

The observed lags correspond to the dips below 100,000 bytes per second shown in Figure 43. Despite the lag, there were no obvious differences in the quality of display on the tablet for all configurations at Level 3.

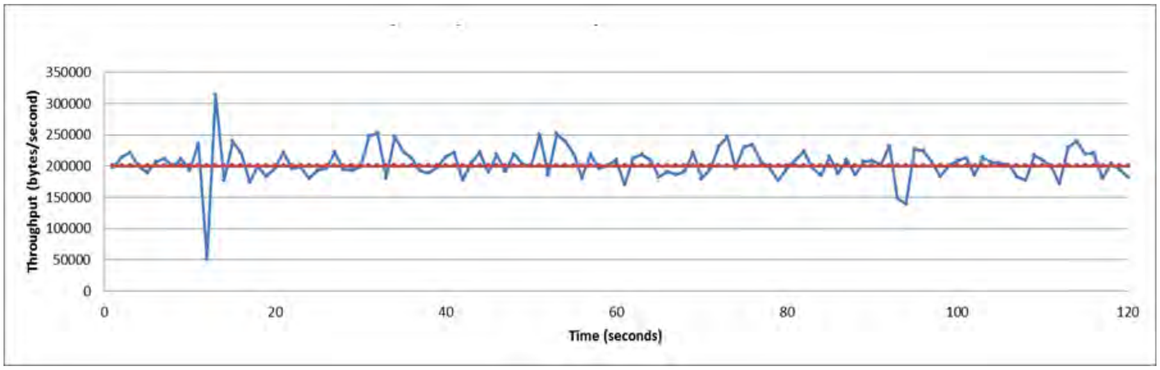

Figure 39. Throughput measured at Level 3 – no repeaters.

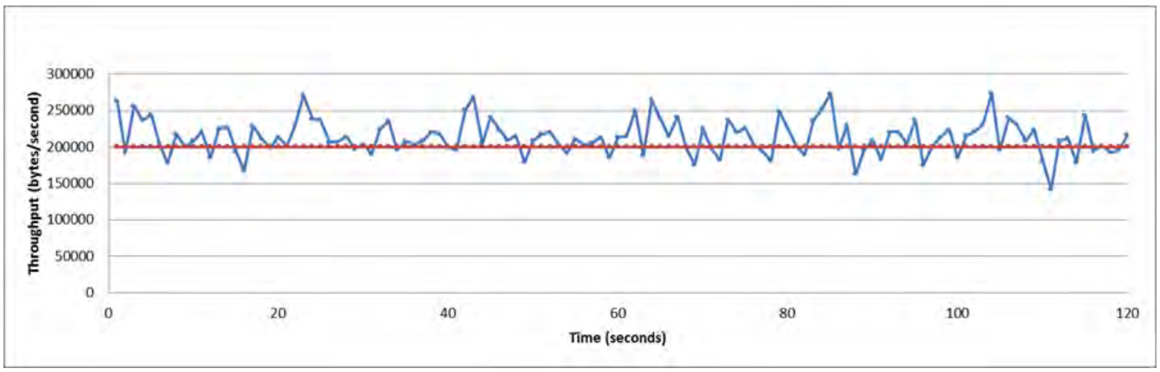

Figure 40. Throughput measured at Level 3 – one repeater at Level 1.5.

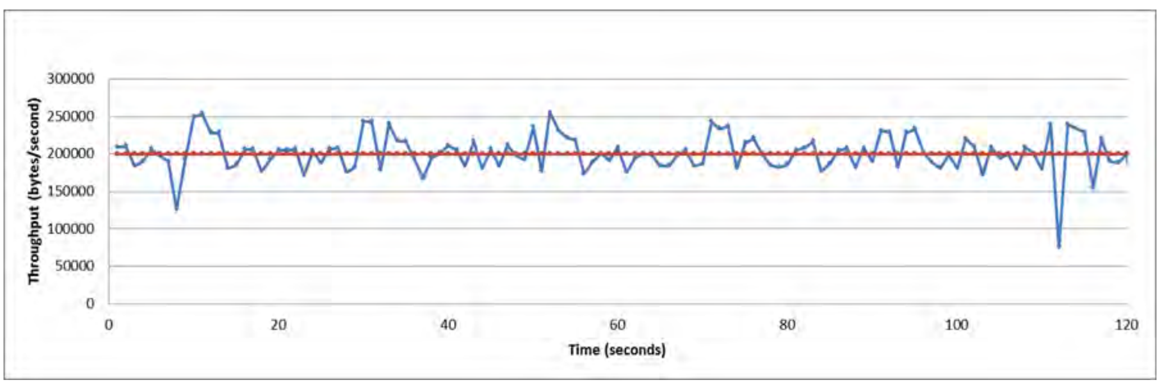

Figure 41. Throughput measured at Level 3 – one repeater at Level 2.5.

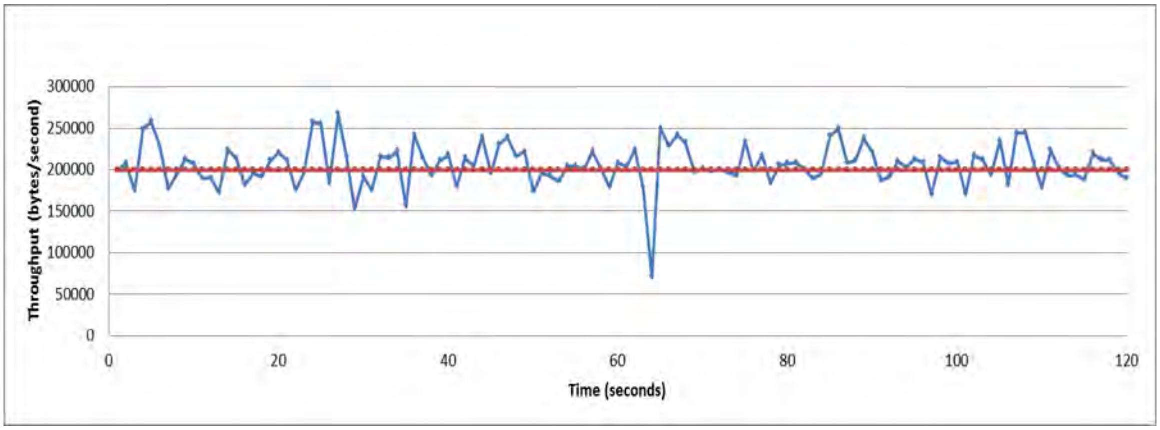

Figure 42. Throughput measured at Level 3 – one repeater at Level 3.5.

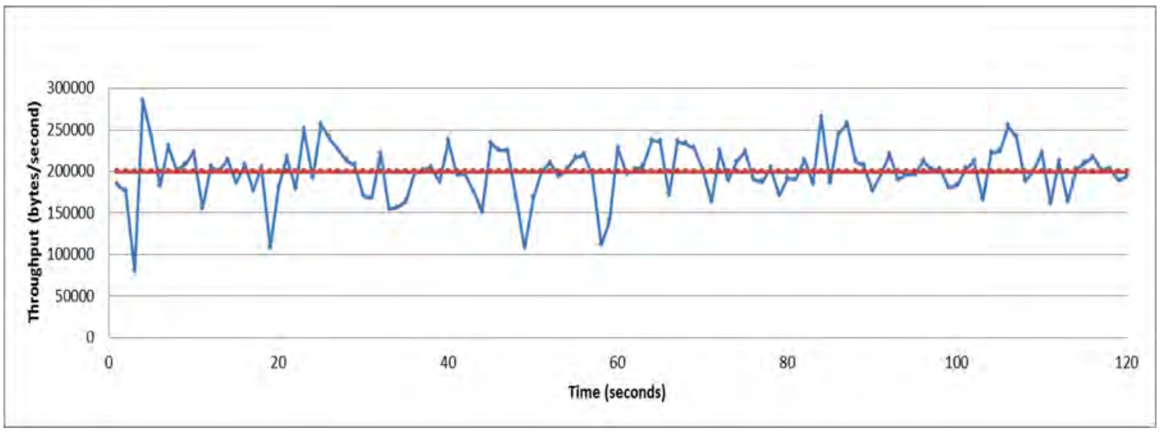

Figure 43. Throughput measured at Level 3 – one repeater at Level 2.5, one repeater at Level 1.5.

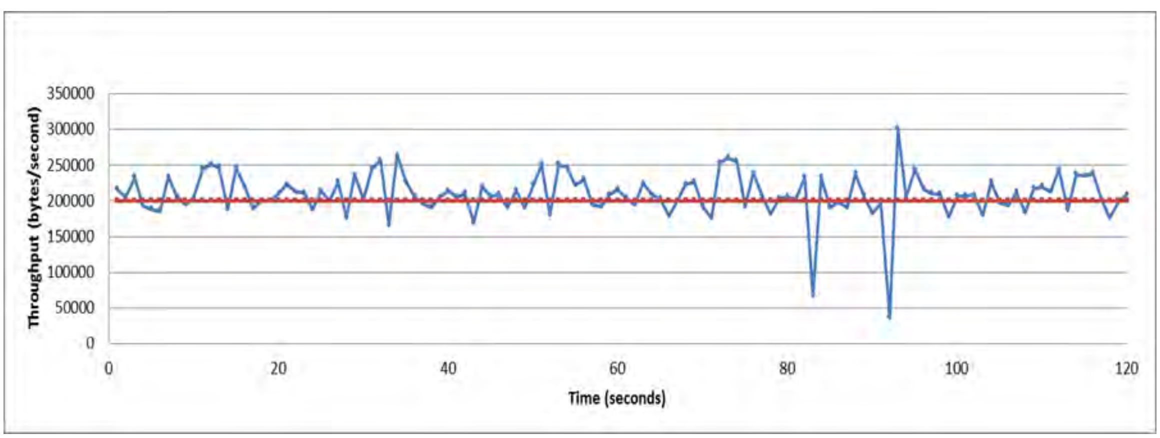

Figure 44. Throughput measured at Level 3 – one repeater at Level 3.5, one repeater at Level 1.5.

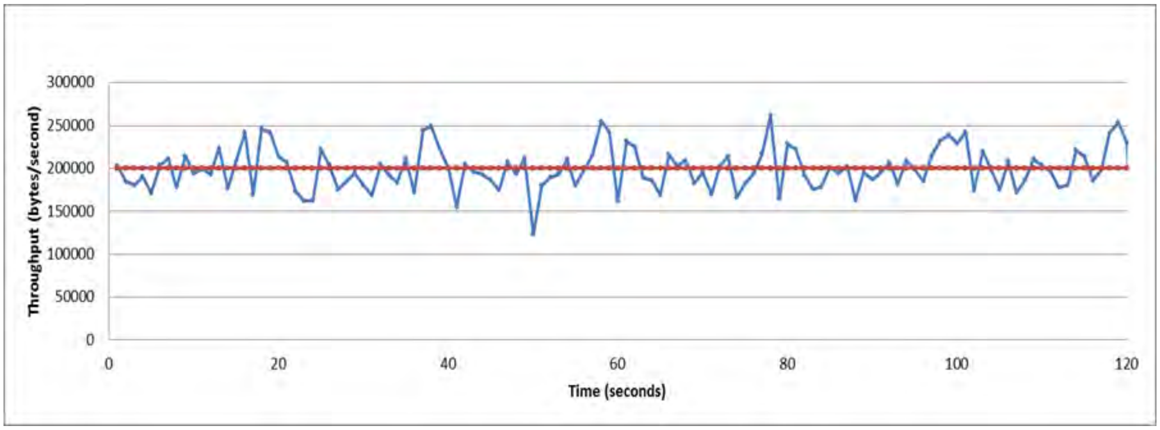

Figure 45. Throughput measured at Level 3 – one repeater at Level 3.5, one repeater at Level 2.5.

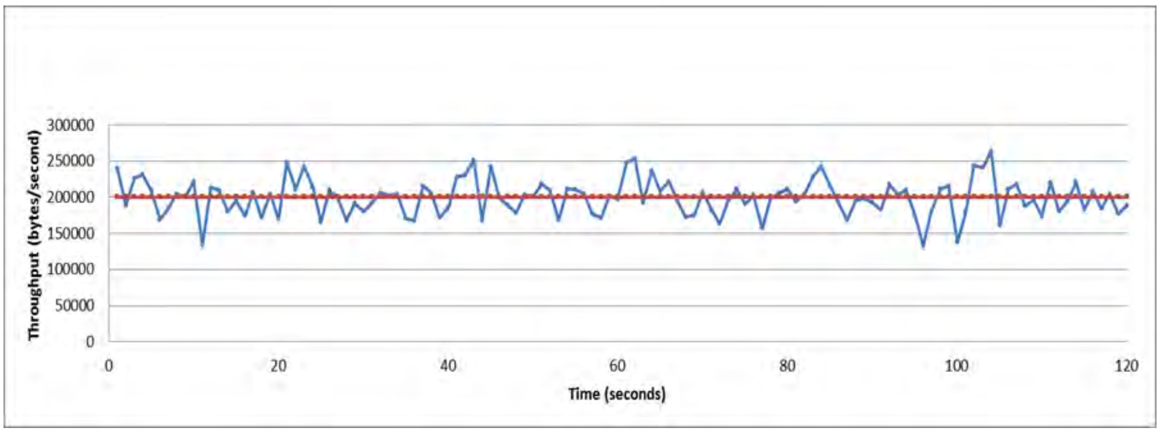

Figure 46. Throughput measured at Level 3 – one repeater at Level 3.5, one repeater at Level 2.5, one repeater at Level 1.5.

4. Readings Measured at Level 2.5

Measurements were collected using the tablet at Level 2.5 for various configurations of the repeaters. Throughput plots for this case are shown in Figure 47 to Figure 54.

The general trend for the throughput for all configurations measured at Level 2.5 hovered about the average baseline value of 200,000 bytes per second. Visually, there were instances of lag observed for the following configurations:

- One repeater at Level 2.5
- One repeater at Level 3.5
- One repeater at Level 2.5, one repeater at Level 1.5
- One repeater at Level 3.5, one repeater at Level 1.5.

The observed lags correspond to the dips below 100,000 bytes per second in Figure 49 to Figure 52. Despite the lags, there were no obvious differences in the quality of display on the tablet for all configurations at Level 2.5.

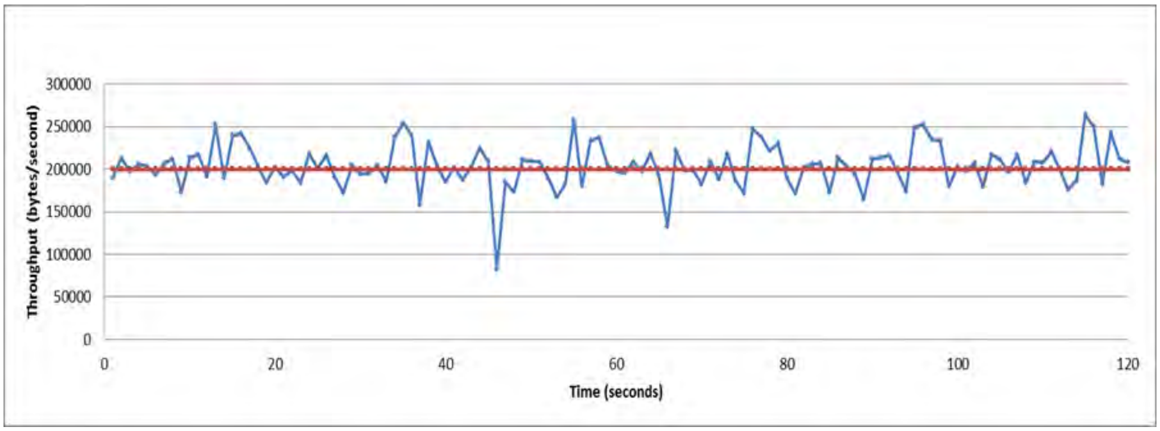

Figure 47. Throughput measured at Level 2.5 – no repeaters.

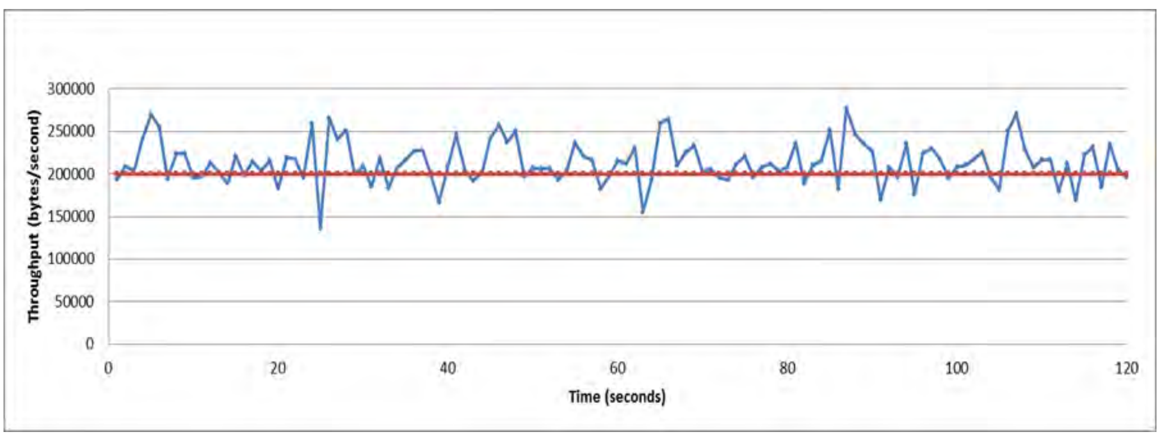

Figure 48. Throughput measured at Level 2.5 – one repeater at Level 1.5.

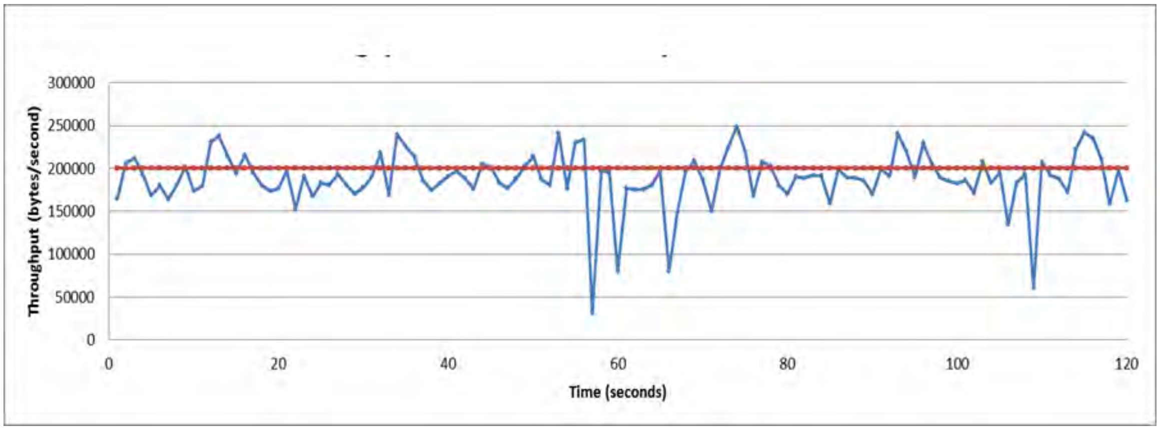

Figure 49. Throughput measured at Level 2.5 – one repeater at Level 2.5.

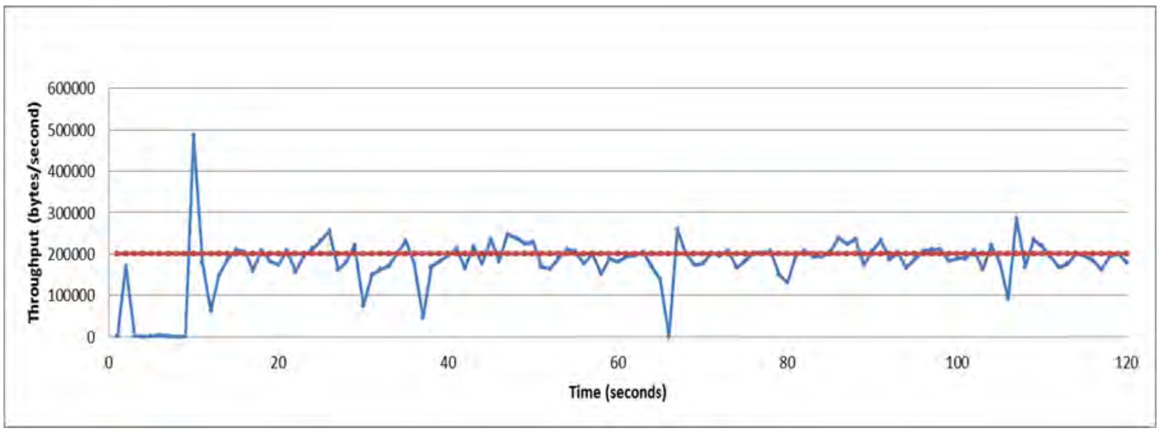

Figure 50. Throughput measured at Level 2.5 – one repeater at Level 3.5.

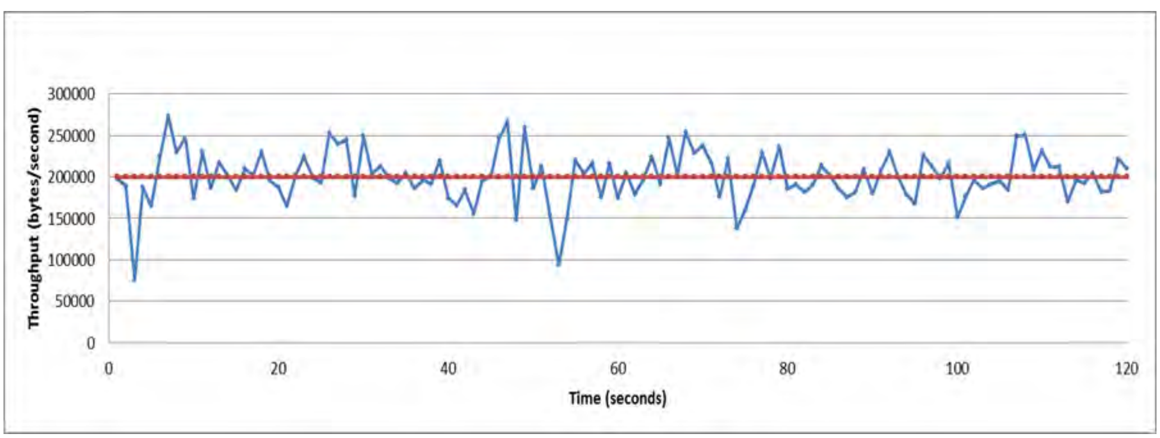

Figure 51. Throughput measured at Level 2.5 – one repeater at Level 2.5, one repeater at Level 1.5.

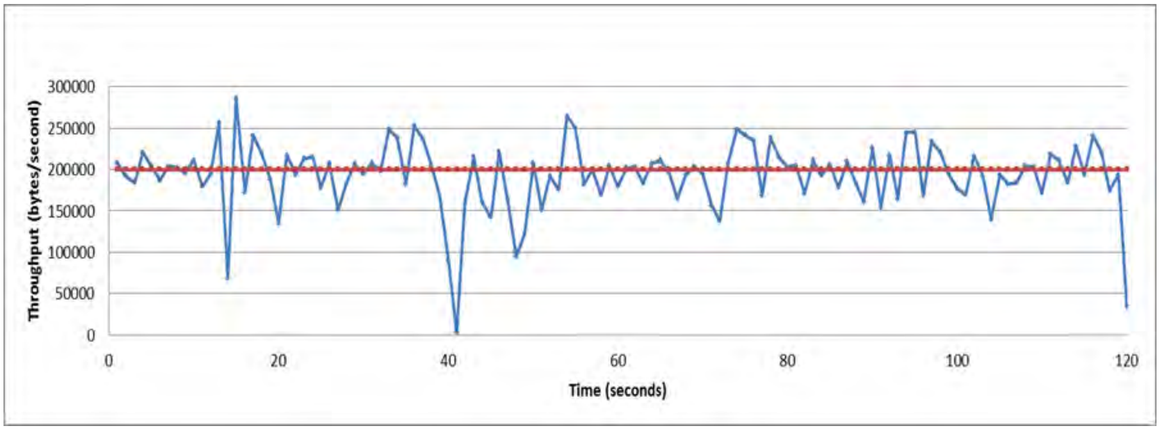

Figure 52. Throughput measured at Level 2.5 – one repeater at Level 3.5, one repeater at Level 1.5.

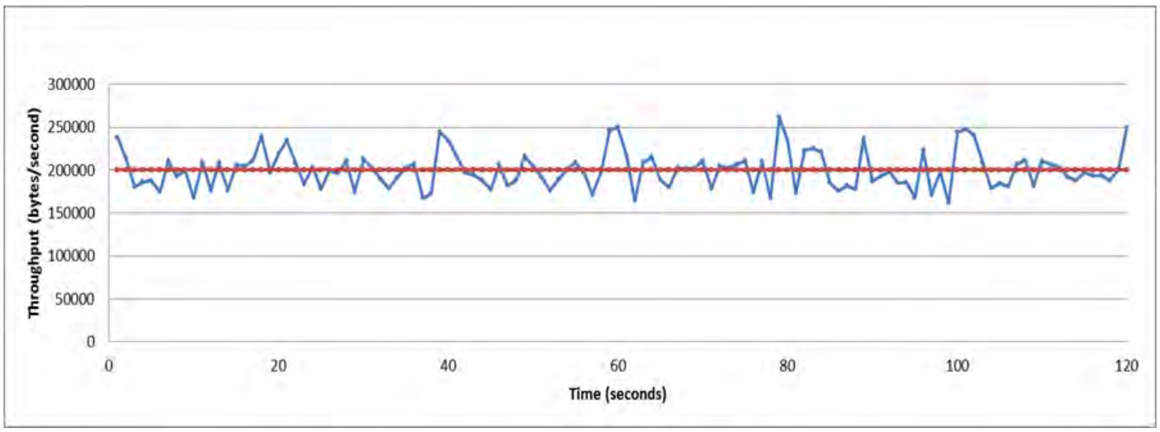

Figure 53. Throughput measured at Level 2.5 – one repeater at Level 3.5, one repeater at Level 2.5.

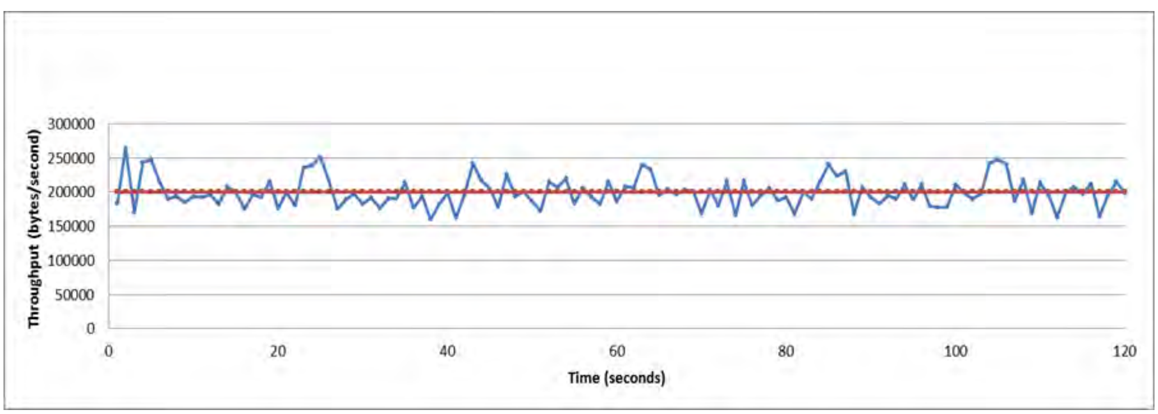

Figure 54. Throughput measured at Level 2.5 – one repeater at Level 3.5, one repeater at Level 2.5, one repeater at Level 1.5.

5. Readings Measured at Level 2

Measurements were collected using the tablet at Level 2, with various configurations of the repeaters.

There were very frequent lags when no repeaters were used. The visually observed lags correspond to the dips below 100,000 bytes per second shown in Figure 55. The other configurations, shown in Figure 56 to Figure 60, also showed lags, though not as frequently as when no repeaters were used. The following configurations, as shown in Figure 61 and Figure 62, showed no lag and had throughput hovering about the average baseline throughput of 200,000 bytes per second:

- One repeater at Level 3.5, one repeater at Level 2.5
- One repeater at Level 3.5, one repeater at Level 2.5, one repeater at Level 1.5.

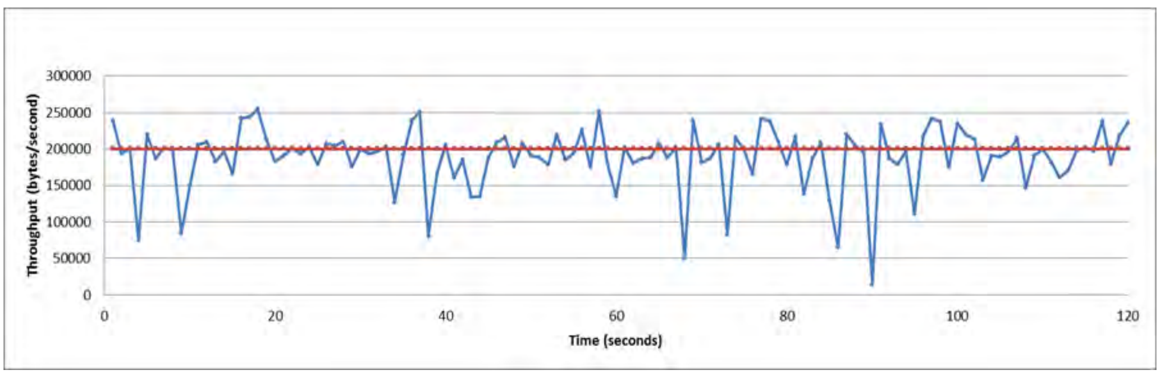

Figure 55. Throughput measured at Level 2 – no repeaters.

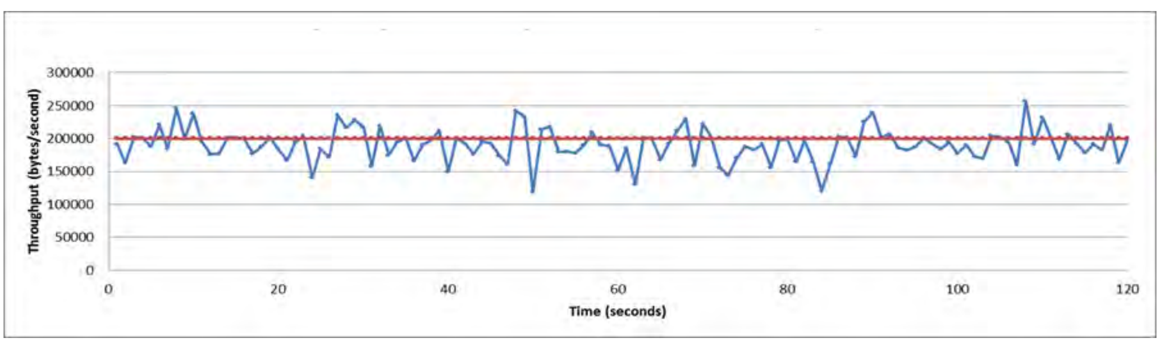

Figure 56. Throughput measured at Level 2 – one repeater at Level 1.5.

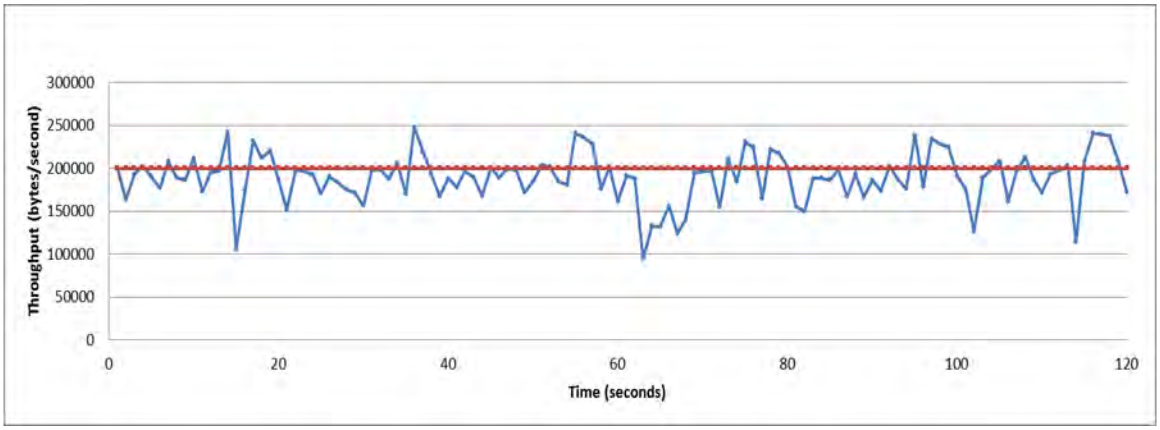

Figure 57. Throughput measured at Level 2 – one repeater at Level 2.5.

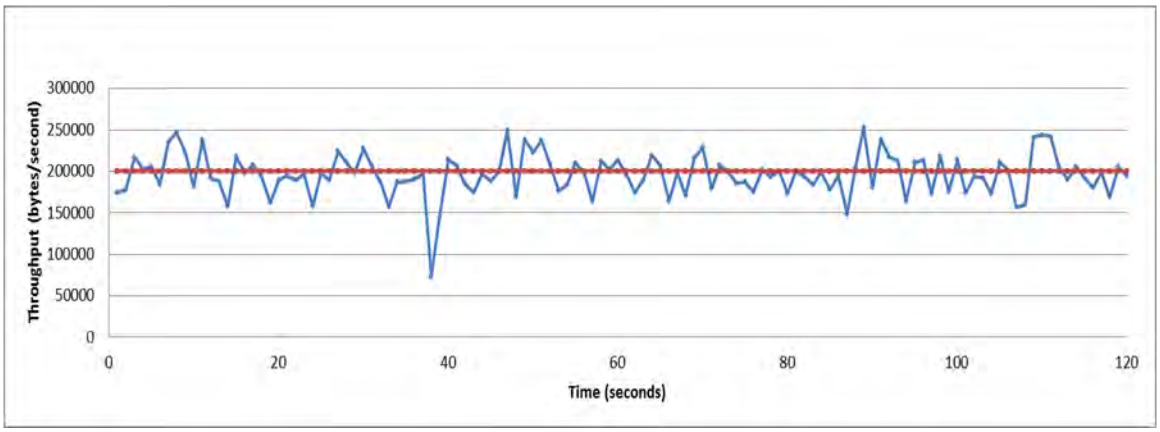

Figure 58. Throughput measured at Level 2 – one repeater at Level 3.5.

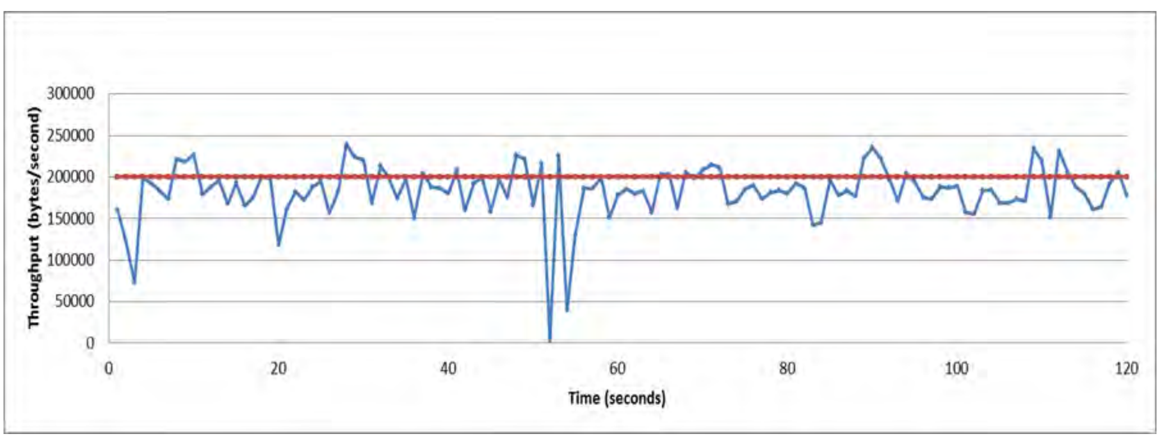

Figure 59. Throughput measured at Level 2 – one repeater at Level 2.5, one repeater at Level 1.5.

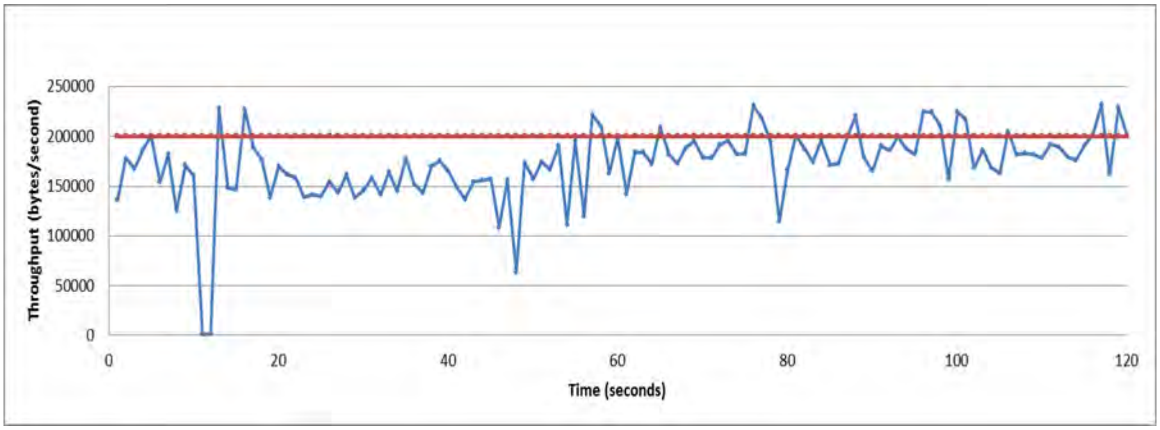

Figure 60. Throughput measured at Level 2 – one repeater at Level 3.5, one repeater at Level 1.5.

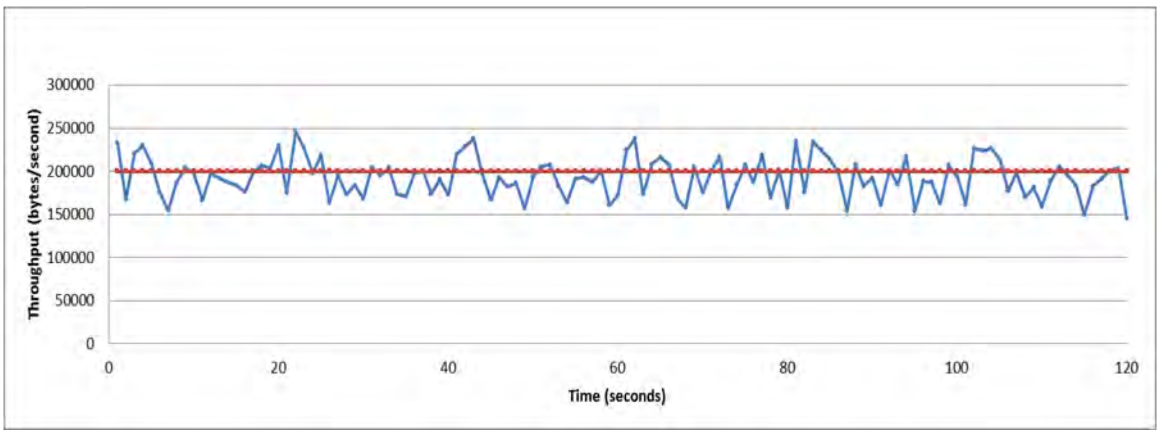

Figure 61. Throughput measured at Level 2 – one repeater at Level 3.5, one repeater at Level 2.5.

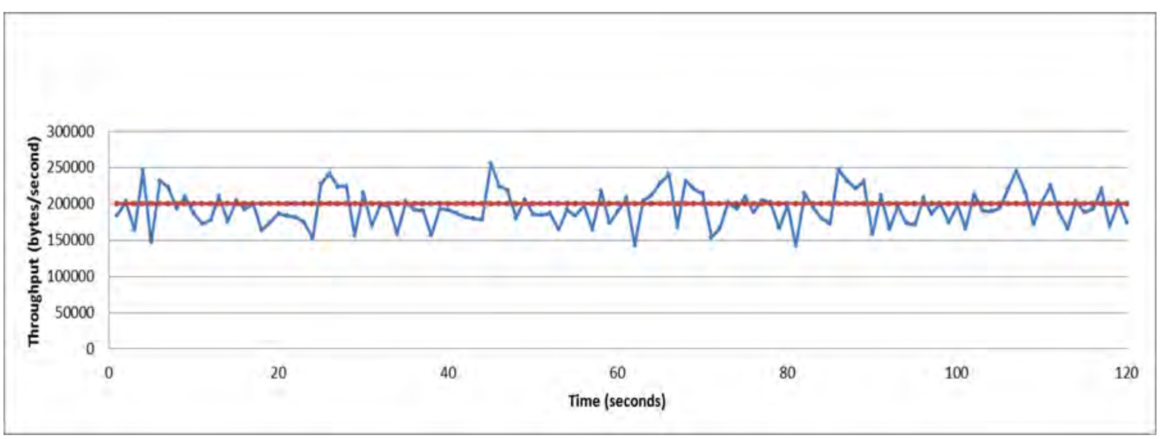

Figure 62. Throughput measured at Level 2 – one repeater at Level 3.5, one repeater at Level 2.5, one repeater at Level 1.5.

6. Readings Measured at Level 1.5

Measurements were collected using the tablet at Level 1.5 for various configurations of the repeaters.

There were very frequent lags and screen freezes when no repeaters were used. The throughput also hovered about 100,000 bytes per second, which is below the average baseline throughput of 200,000 bytes per second, as shown in Figure 63. The other configurations, as shown in Figure 64 to Figure 68, also showed lags, though not as frequently as when no repeaters were used and also had an average throughput that was slightly below the average baseline throughput of 200,000 bytes per second. The following configurations, as shown in Figure 69 and Figure 70, showed no lag and had throughput hovering about the average baseline throughput of 200,000 bytes per second:

- One repeater at Level 3.5, one repeater at Level 2.5
- One repeater at Level 3.5, one repeater at Level 2.5, one repeater at Level 1.5.

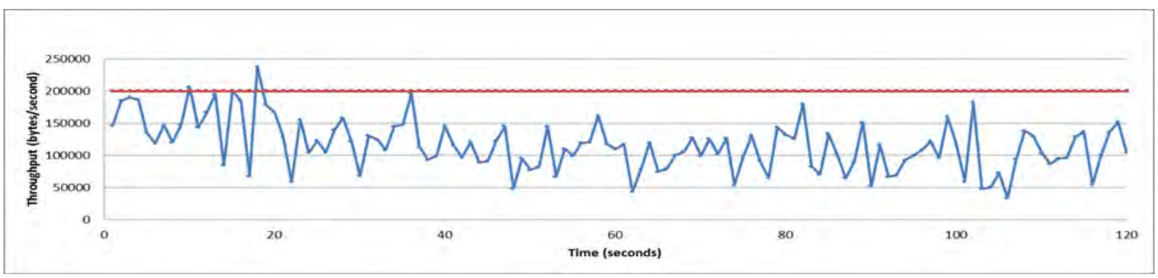

Figure 63. Throughput measured at Level 1.5 – no repeaters.

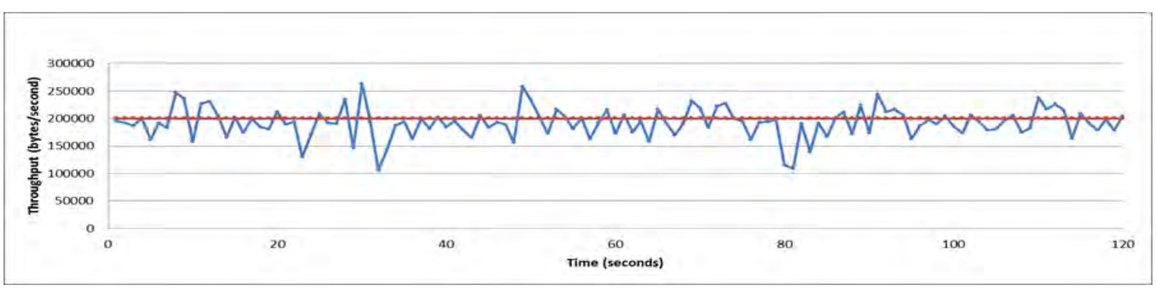

Figure 64. Throughput measured at Level 1.5 – one repeater at Level 1.5.

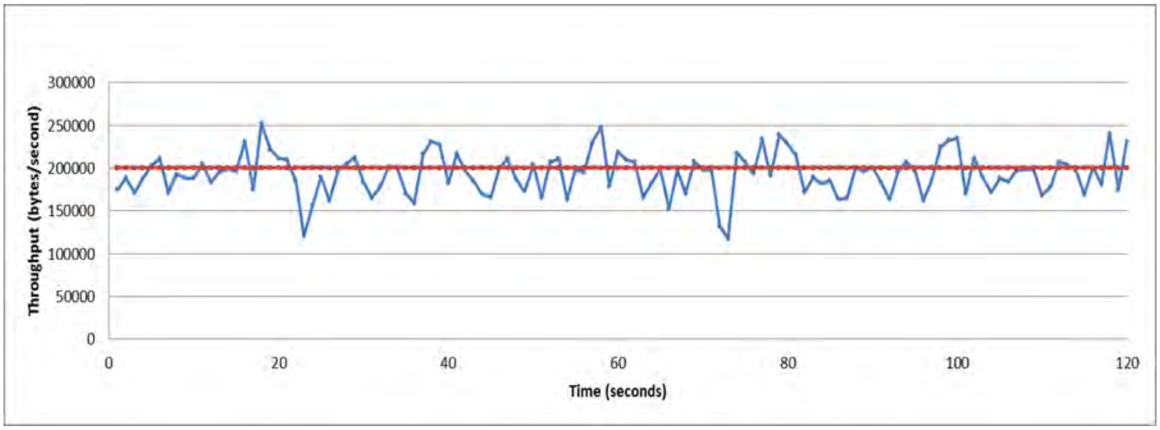

Figure 65. Throughput measured at Level 1.5 – one repeater at Level 2.5.

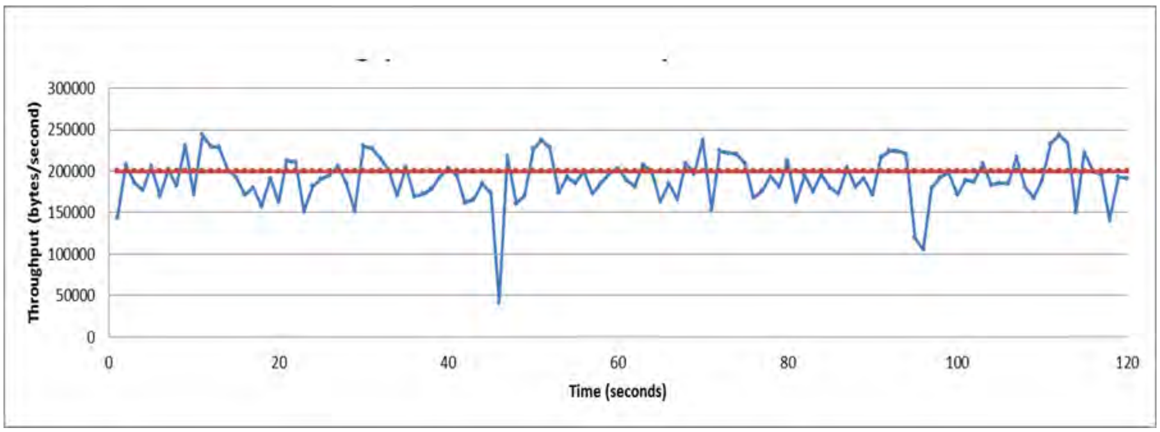

Figure 66. Throughput measured at Level 1.5 – one repeater at Level 3.5.

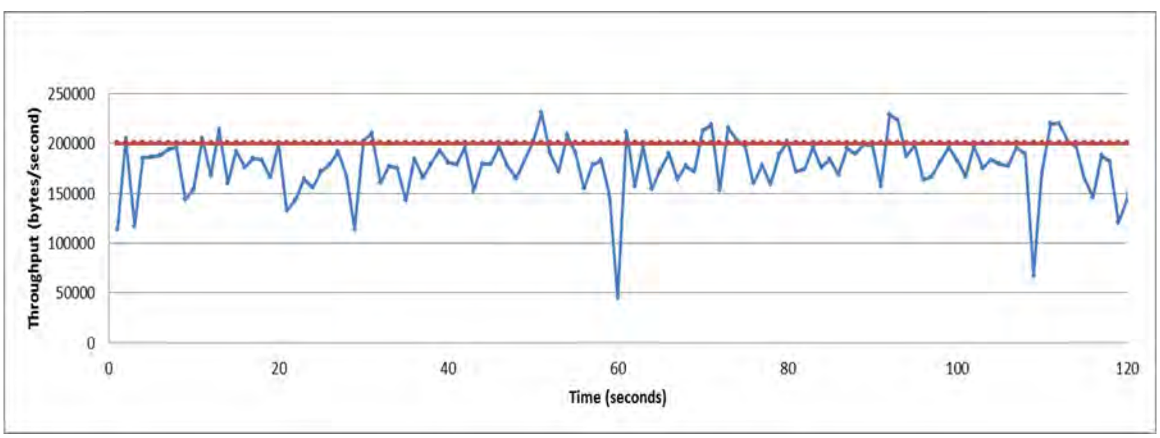

Figure 67. Throughput measured at Level 1.5 – one repeater at Level 2.5, one repeater at Level 1.5.

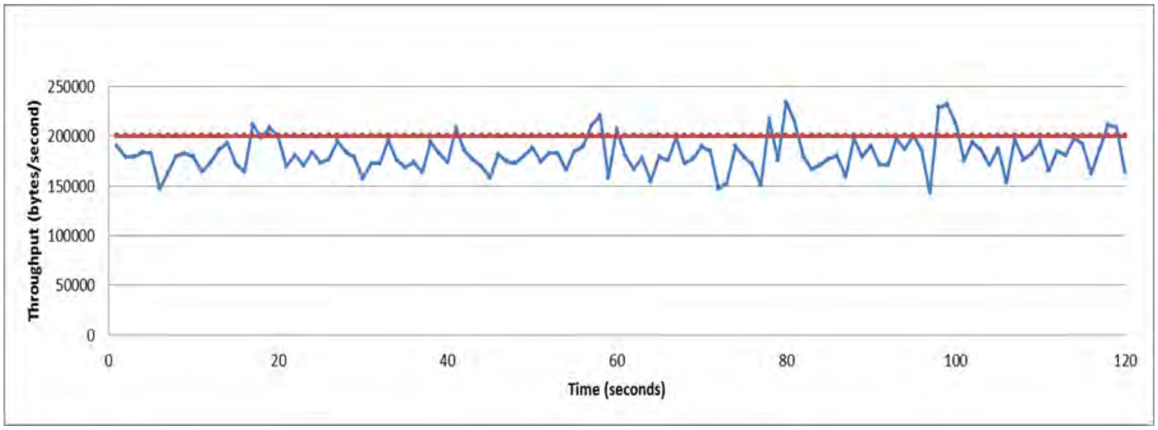

Figure 68. Throughput measured at Level 1.5 – one repeater at Level 3.5, one repeater at Level 1.5.

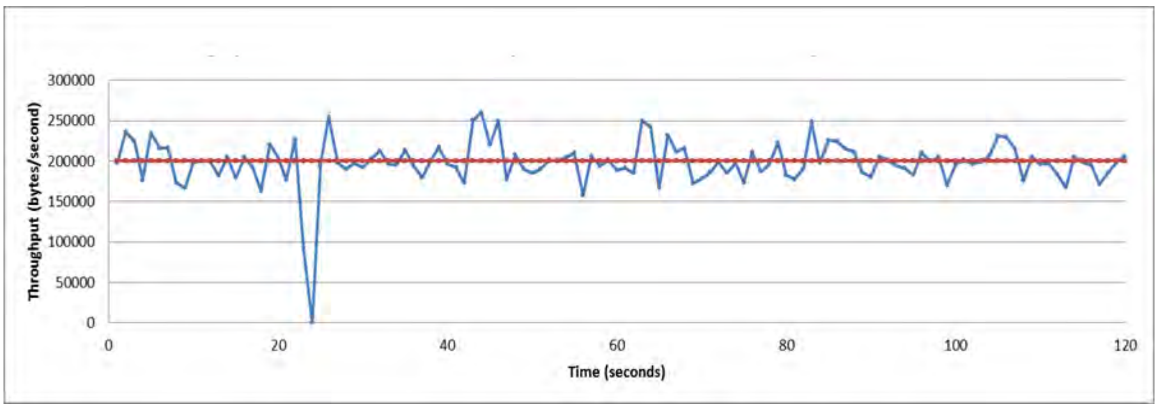

Figure 69. Throughput measured at Level 1.5 – one repeater at Level 3.5, one repeater at Level 2.5.

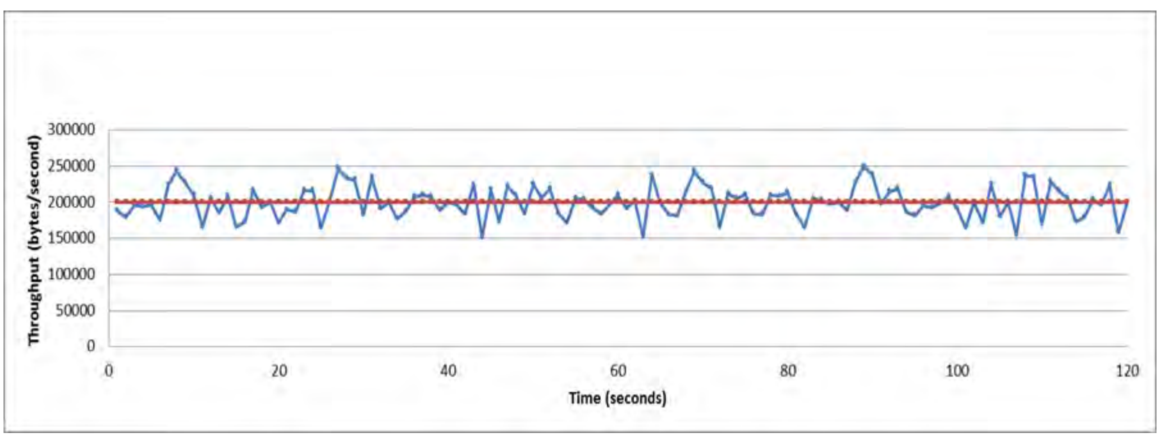

Figure 70. Throughput measured at Level 1.5 – one repeater at Level 3.5, one repeater at Level 2.5, one repeater at Level 1.5.

7. Readings Measured at Level 1

Measurements were collected using the tablet at Level 1 for various configurations of the repeaters.

There were very frequent lags and screen freezes when no repeaters were used. The throughput also fluctuated, averaging about 100,000 bytes per second. This is below the average baseline throughput of 200,000 bytes per second, as shown in Figure 71. The other configurations, as shown in Figure 72 to Figure 76, also showed lags, though not as frequently as when no repeaters were used and also had an average throughput that is slightly below the average baseline throughput of 200,000 bytes per second. The following configurations, as shown in Figure 77 and Figure 78, showed no lag and had throughput hovering about the average baseline throughput of 200,000 bytes per second:

- One repeater at Level 3.5, one repeater at Level 2.5
- One repeater at Level 3.5, one repeater at Level 2.5, one repeater at Level 1.5.

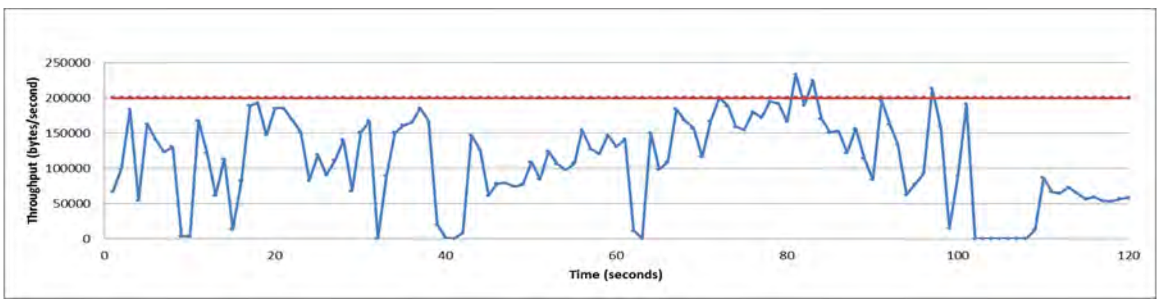

Figure 71. Throughput measured at Level 1 – no repeaters.

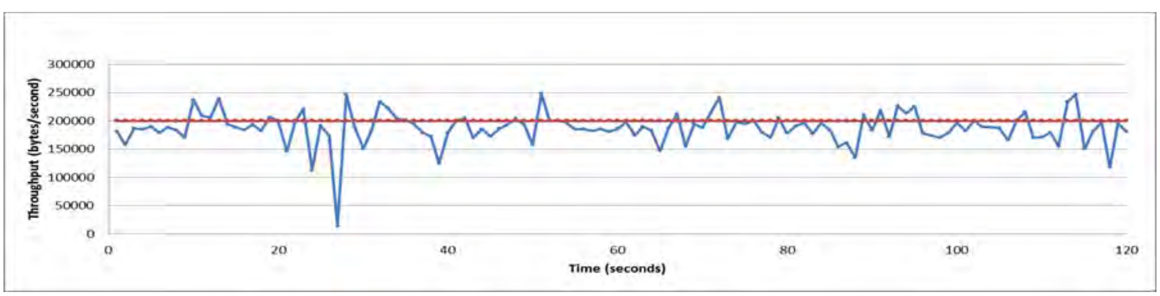

Figure 72. Throughput measured at Level 1 – one repeater at Level 1.5.

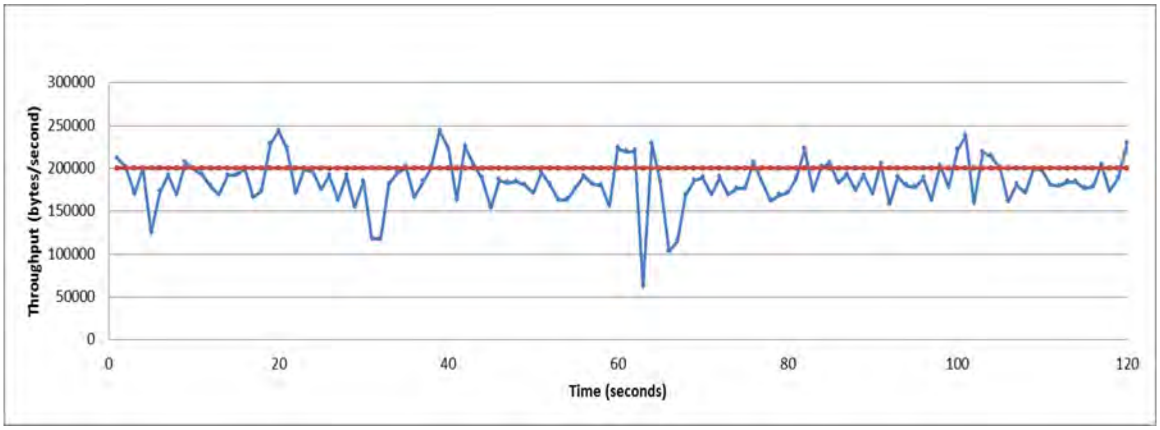

Figure 73. Throughput measured at Level 1 – one repeater at Level 2.5.

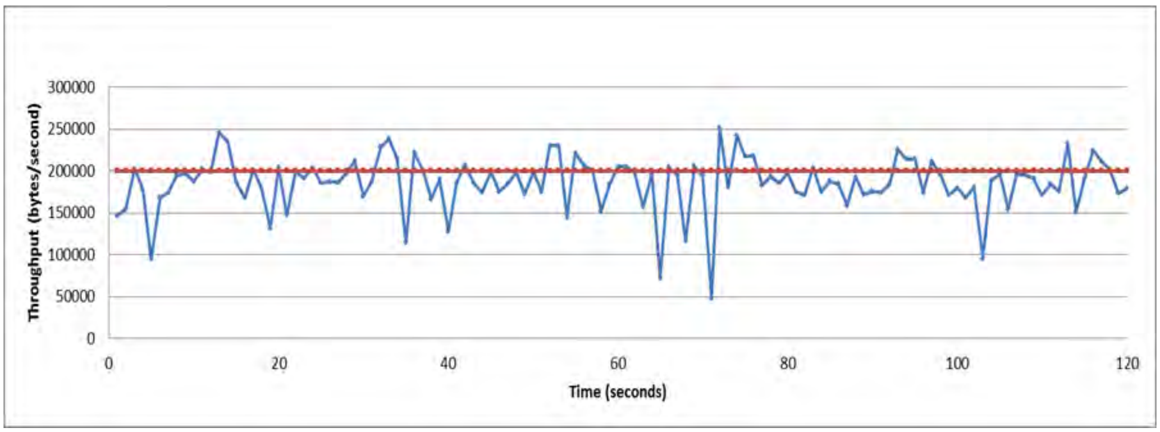

Figure 74. Throughput measured at Level 1 – one repeater at Level 3.5.

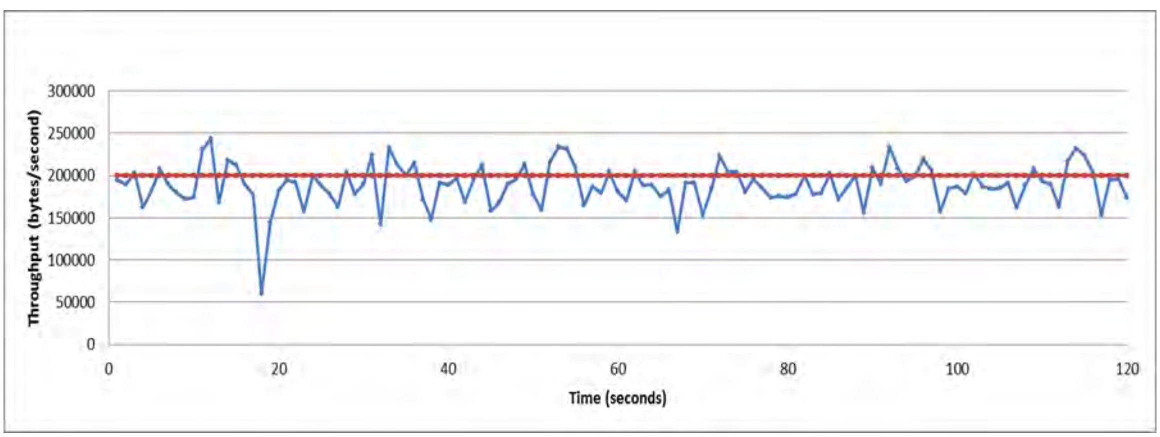

Figure 75. Throughput measured at Level 1 – one repeater at Level 2.5, one repeater at Level 1.5.

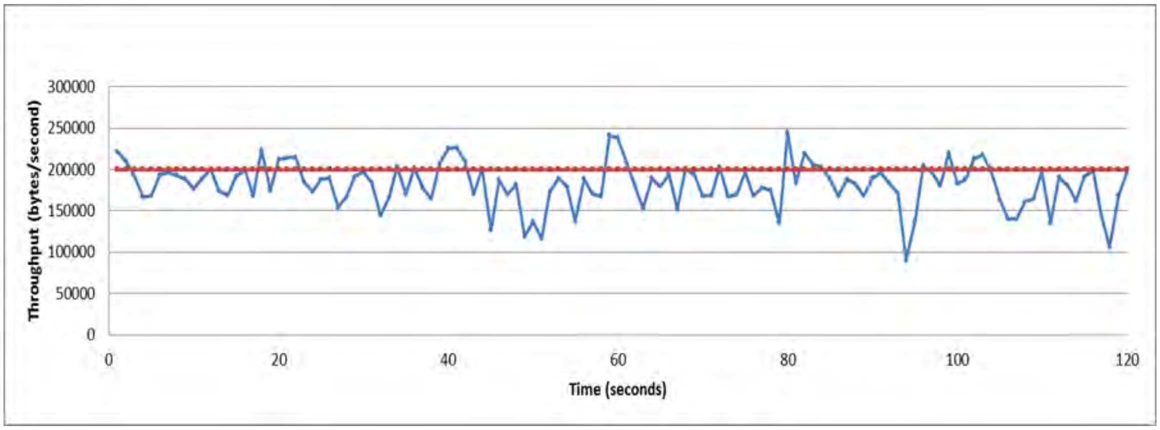

Figure 76. Throughput measured at Level 1 – one repeater at Level 3.5, one repeater at Level 1.5.

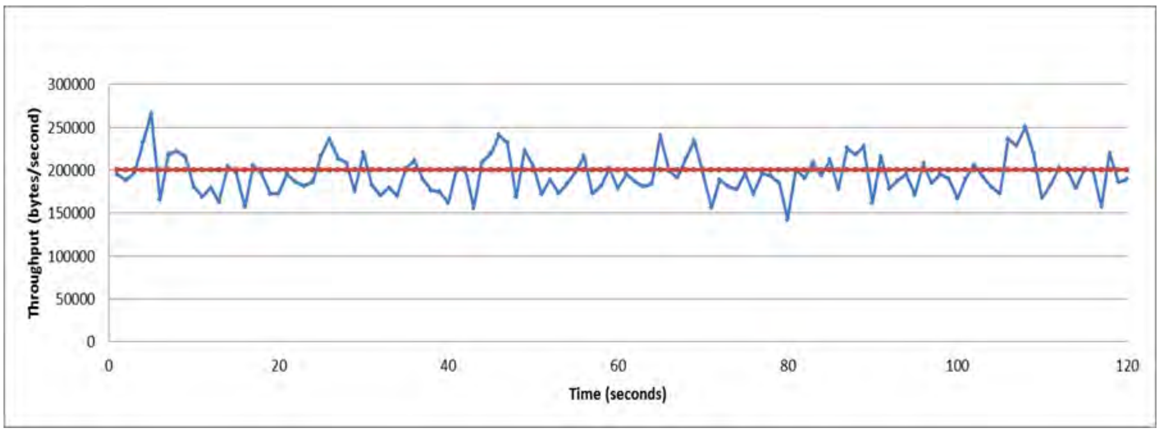

Figure 77. Throughput measured at Level 1 – one repeater at Level 3.5, one repeater at Level 2.5.

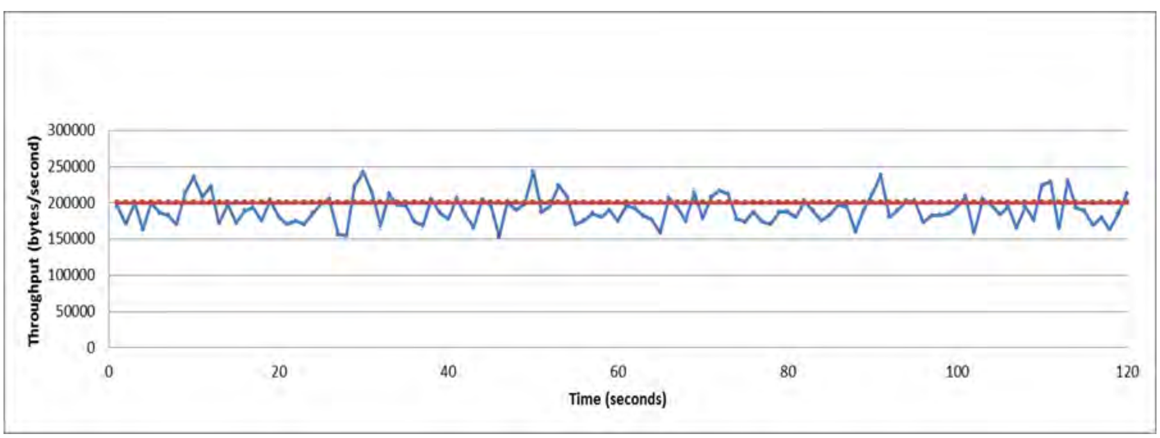

Figure 78. Throughput measured at Level 1 – one repeater at Level 3.5, one repeater at Level 2.5, one repeater at Level 1.5.

D. SUMMARY

A summary of the repeater configurations and the location where the throughput measurement was taken is shown in **Error! Reference source not found.**. The observations are grouped into three categories, good, average, and poor, with the following definitions:

- Good – Throughput fluctuates about the average baseline throughput of 200,000 bytes per second, with no dips.
- Average – Throughput fluctuates about the average baseline throughput of 200,000 bytes per second, with occasional dips.
- Poor – Throughput fluctuates below the average baseline throughput of 200,000 bytes per second, or with frequent dips.

Table 1. Summary of repeater configurations and throughput measurements at various levels.

Level ***	No rept*	One rept* at Level 1.5	One rept* at Level 2.5	One rept* at Level 3.5	Two rept*: One at Level 2.5 and one at Level 1.5	Two rept*: One at Level 3.5 and one at Level 1.5	Two rept*: One at Level 3.5 and one at Level 2.5	Three rept*: One at Level 3.5, one at Level 2.5 and one at Level 1.5
4	Good	Good	Good	Good	Good	Good	Good	Good
3.5	Good	Good	Good	Good	Good	Good	Good	Good
3	Good	Good	Good	Good	Poor	Good	Good	Good
2.5	Avg**	Avg**	Poor	Poor	Poor	Poor	Good	Good

Level ***	No rept*	One rept* at Level 1.5	One rept* at Level 2.5	One rept* at Level 3.5	Two rept*: One at Level 2.5 and one at Level 1.5	Two rept*: One at Level 3.5 and one at Level 1.5	Two rept*: One at Level 3.5 and one at Level 2.5	Three rept*: One at Level 3.5, one at Level 2.5 and one at Level 1.5
2	Poor	Avg**	Avg**	Avg**	Avg**	Poor	Good	Good
1.5	Poor	Avg**	Avg**	Avg**	Avg**	Good	Good	Good
1	Poor	Avg**	Avg**	Avg**	Avg**	Avg**	Good	Good

* Rept represents repeater

** Avg represents average

*** Level indicates where the tablet was located

From **Error! Reference source not found.**, we observe that repeaters, in general, improve the range of the network. The worst configuration, which is the configuration without repeaters, has the display on the tablet showing more lag and screen freeze from Level 2 onwards.

When one repeater is used, the most optimal configuration is:

- One repeater at Level 1.5.

It is not better than the other two configurations and, hence, it is not conclusive that using one repeater at Level 1.5 is definitely better.

When two repeaters are used, the most optimal configuration is:

- One repeater at Level 3.5, one repeater at Level 2.5.

This observation is consistent throughout all throughput measurements. This is expected since having the first repeater at Level 3.5 results in a stronger signal than having the first repeater at Level 2.5 since there is less free space loss. Subsequently, the second repeater at Level 2.5 also receives a stronger signal than when the second repeater is at Level 1.5 for the same reason.

Finally, having three repeaters in the network produced similar results as the configuration with two repeaters – one repeater at Level 3.5, one repeater at Level 2.5.

The distribution of TCP parameters, such as lost segments, duplicate ACKs, retransmissions and fast retransmissions for various configurations is shown in Figure 79 to Figure 86. Each graph shows the TCP parameters for a specific configuration of repeaters, measured from Level 4.5 to Level 1, i.e., from the nearest to the furthest from the wireless AP. The *x*-axis shows the time at which the experiment was conducted, moving from Level 4.5 to Level 1:

- 0 to 120 s – Level 4.5
- 140 to 260 s – Level 4
- 280 to 400 s – Level 3.5
- 420 to 540 s – Level 3
- 560 to 680 s – Level 2.5
- 700 to 820 s – Level 2
- 840 to 960 s – Level 1.5
- 980 to 1100 s – Level 1.

When no repeaters were used, the TCP parameters appeared with higher intensity as the tablet is further from the wireless AP, as shown in Figure 79. This is consistent with the measured throughput, where the throughput drops as the tablet moves further from the wireless AP.

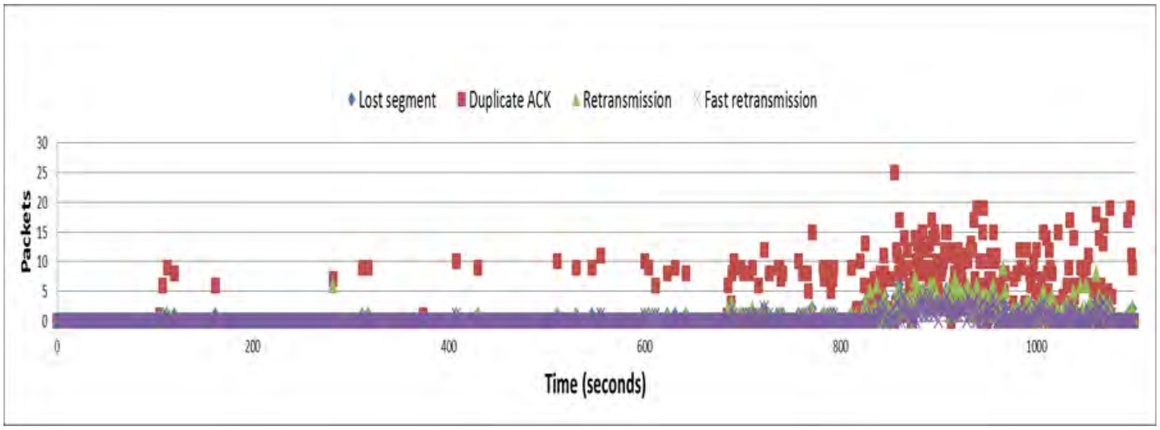

Figure 79. TCP parameters when no repeaters are used.

When one repeater is used, the TCP parameters appear more frequently as the tablet is further from the wireless AP but with lower intensity than when no repeaters are used. This is observed in Figure 80 to Figure 82.

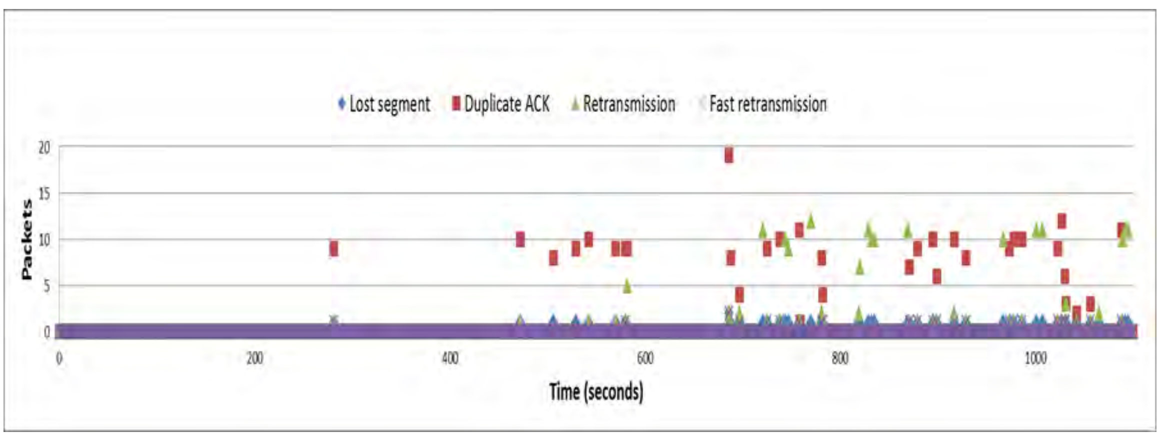

Figure 80. TCP parameters when one repeater is placed at Level 1.5.

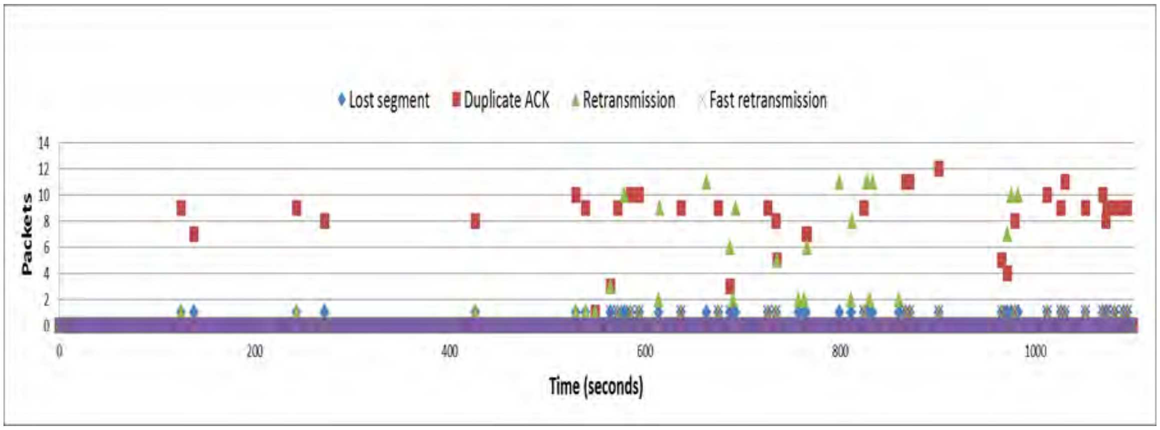

Figure 81. TCP parameters when one repeater is placed at Level 2.5.

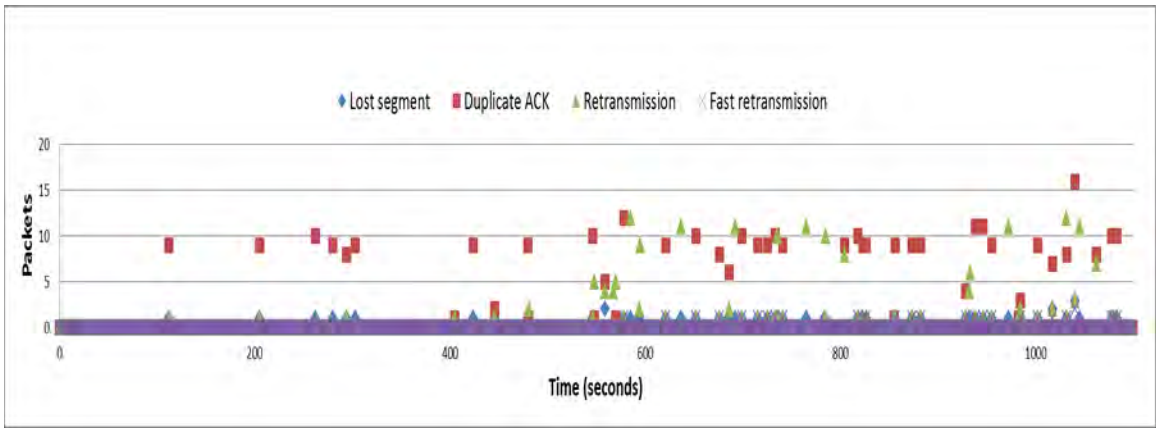

Figure 82. TCP parameters when one repeater is placed at Level 3.5.

When two repeaters were used, the TCP parameters occurred at varying intensity, depending on how the repeaters were spaced. For the configuration where one repeater was placed at Level 2.5 and one repeater was placed at Level 1.5, as shown in Figure 83, the TCP parameters occurred in greater intensity when the tablet was nearer the wireless AP and decreased in intensity at approximately 700 s, which corresponds to Level 2. This could be due to the received signal being weaker due to the first repeater being placed further at Level 2.5 as compared to the other configurations where the first repeater was at Level 3.5. For the configuration where one repeater is placed at Level 3.5 and one repeater was placed at Level 1.5, as shown in Figure 84, the intensity of the

TCP parameters was mostly concentrated from the 560 s to 700 s, which corresponds to Level 2.5. This may be due to the signal from the first repeater at Level 3.5 weakening before it reaches the second repeater at Level 1.5. For the configuration where one repeater was placed at Level 3.5 and one repeater was placed at Level 2.5, as shown in Figure 85, the intensity of the TCP parameters were evenly distributed throughout the different levels. It was the most optimal configuration for two repeaters.

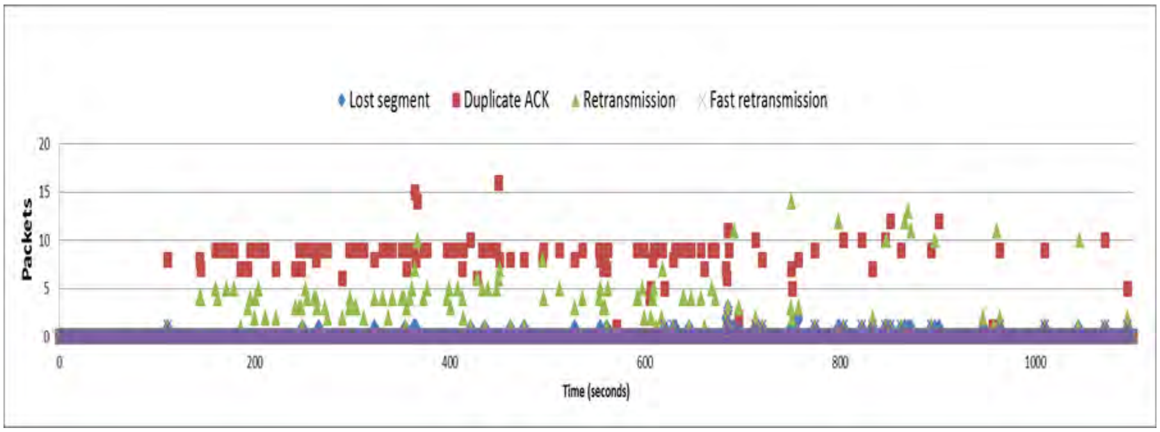

Figure 83. TCP parameters when one repeater is placed at Level 2.5 and one repeater is placed at Level 1.5.

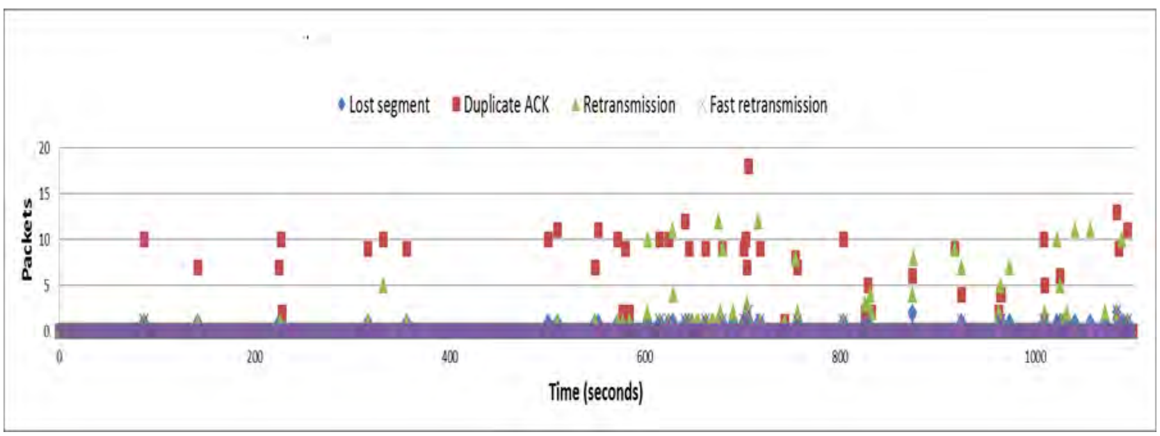

Figure 84. TCP parameters when one repeater is placed at Level 3.5 and one repeater is placed at Level 1.5.

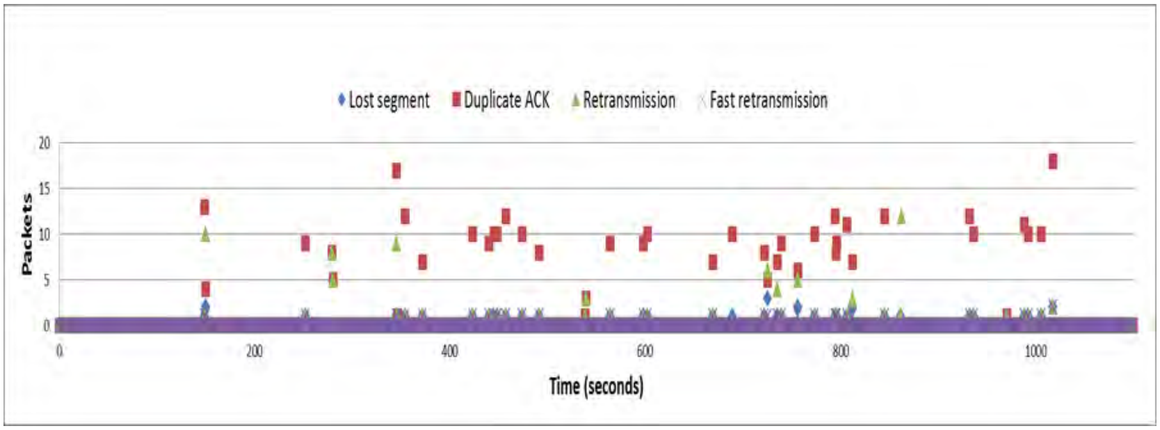

Figure 85. TCP parameters when one repeater is placed at Level 3.5 and one repeater is placed at Level 2.5.

Lastly, the configuration with three repeaters showed the fewest occurrences of the TCP parameters, as shown in Figure 86.

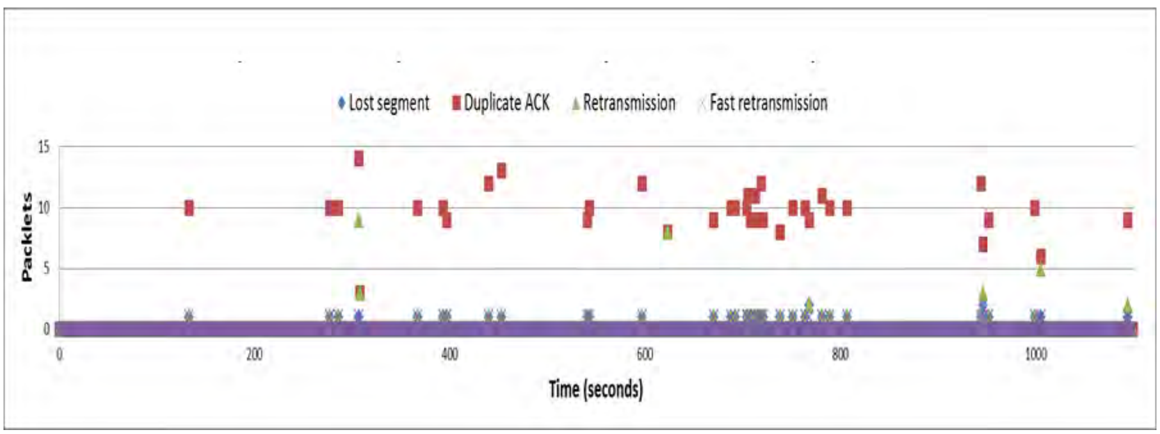

Figure 86. TCP parameters when one repeater is placed at Level 3.5, one repeater is placed at Level 2.5 and one repeater is placed at Level 1.5.

The number of occurrences of the TCP parameters is tabulated in **Error! Reference source not found.**. Consistent with the observations from the throughput measurements, the worst performance occurred when no repeaters were used, and the best performance occurred when three repeaters were used.

Table 2. Summary of number of lost segments, duplicate ACKs, retransmissions and fast retransmissions for various repeaters configuration.

	Lost segments (packets)	Duplicate ACKs (packets)	Retransm-issions (packets)	Fast retransm-issions (packets)
No rept*	559	2086	638	304
One rept* at Level 1.5	48	272	200	26
One rept* at Level 2.5	49	303	170	26
One rept* at Level 3.5	58	367	198	28
One rept* at Level 2.5, one rept* at Level 1.5	57	1033	488	23
One rept* at Level 3.5, one rept* at Level 1.5	60	358	230	27
One rept* at Level 3.5, one rept* at Level 2.5	43	370	99	36
One rept* at Level 3.5, one rept* at Level 2.5, one rept* at Level 1.5	37	361	62	35

* Rept represents repeater

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V. CONCLUSION AND RECOMMENDATIONS

A. SUMMARY

In summary, the proposed concept of operation addresses U.S. Navy's concern to reduce crew size without increasing labor hours since manpower is reduced from two technicians to one technician for the proposed calibration process. It takes into consideration the possible constraints posed by the ship's layout and sets up a temporary wireless network to avoid the laying of cables. This temporary wireless network does not interfere with U.S. Navy's network security since it does not use the shipboard's LAN for data transmission. The use of the KVM switch with an embedded VNC server software also allows viewing access to the MCS system console without requiring user authentication from the U.S. Navy.

In this thesis, experiments with different configurations of repeaters and locations were conducted to determine the feasibility of using repeaters to extend the network range. The results from the experiments showed that when the maximum number of repeaters were used, i.e., three repeaters, the performance was on par with the best configuration of two repeaters used and better than the performance when one or no repeaters were used. No signs of degradation were observed when three repeaters were used. By inference, this setup is not limited to just three repeaters.

Even in the case for the worst performance configuration, i.e., no repeaters used, the display on the tablet still updated within five seconds through visual observations, even though it was accompanied by lags and screen freezes.

The experiments showed that repeaters were able to increase the network range without degradation of throughput for this application's bandwidth requirement if placed at optimal positions. This concept of using COTS 802.11 wireless devices to transmit the MCS system console's display to the technician manning the reference sensor instrument’s readout is feasible for the purpose of checking for steady-state outputs but not the transient response of the sensor.

B. FUTURE WORK

The work conducted in this thesis was an initial feasibility test to demonstrate that repeaters can be added to a wireless network to increase the network range without degradation of throughput. It also showed that even with the same number of repeaters in the wireless network, the placement of the repeaters makes a difference to the network statistics. Further testing is necessary to investigate this concept of operation in an environment that is closer to the shipboard setting.

The location for conducting this experiment was in the Naval Postgraduate School’s Spanagel Hall. Future experiments can be conducted in another location to determine if the collected network statistics are similar. The ideal location for testing, if possible, would be to conduct the experiment in a ship.

The methodology of conducting this experiment in the stairways was to permutate the number and location of the three repeaters. This resulted in a systematic collection of network statistics to analyze the impact of the number and location of the repeaters. This can be used as a baseline for future testing; however, placing the wireless AP and tablet at the stairways is not a practical scenario in a shipboard setting. In a shipboard setting, the wireless AP and tablet are likely to be in different levels of a hallway. The experimental setup can be such that the wireless AP and tablet are fixed at different levels in a building or ship, and the number and location of repeaters are modified until communications is established between the wireless AP and tablet.

LIST OF REFERENCES

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